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JP-8+100 ENGINE DEMONSTRATION
Industry Version

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NOTICE

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

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14. ABSTRACT

The effects of JP-8+100 fuel were investigated to (1) identify and perform development work needed to accelerate the transition of JP-8+100 fuel to field use, (2) evaluate the cost effectiveness of using this fuel to reduce maintenance related to fuel fouling/coking in existing aircraft, and (3) assess the performance of JP-8+100 in current and future advanced high-performance engines and aircraft fuel systems.

The additive selected by the Air Force was BetzDearborn Spec Aid 8Q462. The selected additive did not have any effect on endurance-engine hot sections. Maintenance records for Air National Guard squadrons were reviewed, and no evidence was found that the additive caused any change in the flight abort rate or was a reason for flight aborts. Fuel thermal-stability testing showed that additive increased fuel temperature capability. It was concluded that JP-8+100 would be safe to use in the field.

15. SUBJECT TERMS
aircraft gas turbines, fuel, aviation gas turbine fuel, JP-8, fuel fouling, coking, combustion, fuel thermal stability, JP-8+100

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Preface

This final report is submitted by GE Aircraft Engines (GEAE) located at Evendale, Ohio. The work was conducted under Contract F33615-95-C-2508. Contract sponsorship and guidance was provided by the Propulsion Directorate, Air Force Research Laboratory (AFRL), United States Air Force, Wright Patterson Air Force Base, Ohio, 45433-7103. The Government Project Engineer was Mrs. Patricia (Liberio) Pearce.

For GEAE, Mr. S. Seto served as program manager and supervised the small-scale component testing, and Mr. P. Dom conducted hardware design studies and hardware purchases.

Dr. C. Moses and Mr. R. Alvarez, of Southwest Research Institute (SwRI), conducted the Base Maintenance Studies and Fuel Thermal Stability studies.

1.0 Summary

The purpose of the work reported herein was to determine the suitability of the thermal-stability additives for use in GEAE gas turbine engines. Although selection of the additive(s) was not based solely on this work, rejection of the additive(s) could have been.

The program started with the objective of running the additive(s) in each of two GEAE Engine Models: the F110-GE-100 and the F101-GE-102. At the completion of the program, the additive selected by the Air Force Fuels Branch had been run in three F110 engine models and the TF39 for a total of 2100 engine endurance hours.

Further, over the time period of the program, significant field experience was obtained from service evaluation by Air National Guard units flying GEAE engines: TF-34 high-bypass turbofans, F110-100 augmented turbofans, T64 turboshafts, and T700 turboshafts. During this operational time, several controls, fuel pumps, and sets of fuel nozzles were inspected from factory and field engines. These inspections revealed no significant effects from the use of the additive.

Small-scale tests were run to determine the effects of the additives on corrosion and erosion rates of typical turbine materials. These tests indicated that the additive would increase these rates relative to neat fuel, but the rates noted, coupled with the engine service data, indicated that the additive would have only a slight effect on hot-parts life.

Small-scale tests were run to determine the effects of the additive on fuel thermal stability (resistance to fuel coking). In fuels with marginal stability, the additive increased resistance to internal coking.

The additive selected by the Fuels Branch, BetzDearborn SPEC AID 8Q462, has been approved for use in GEAE and CFMI engines.

2.0 Introduction

GE Aircraft Engines (GEAE) conducted a research program into the effects of JP-8+100 fuel on the F110 and F101 engine models. The engine-endurance demonstrations of JP-8+100 fuel were conducted. The objectives were to (1) identify and perform development work needed to accelerate the transition of JP-8+100 fuel to field use, (2) evaluate the cost effectiveness of using this fuel to reduce maintenance related to fuel fouling/coking in existing aircraft, and (3) assess the performance of JP-8+100 in current and future advanced high-performance engines and aircraft fuel systems. The technical program was started in June 1995 and completed in July 2000. It was performed under the guidance of Mrs. Patricia (Liberio) Pearce, USAF Fuels Branch.

Results of this work indicated that the presence of the selected additive in JP-8 fuel did not have any effect on endurance-engine hot sections (combustor, turbines, rear frame, and augmentors — if present). Therefore, it was concluded that JP-8+100 would be safe to use in the field. Engines tested were the F110-GE-129, F110-GE-100, F110-GE-400, TF39-GE-100, and some very limited time on an F101-GE-102. Inspection of several engine fuel-wetted components (such as main fuel controls, fuel pumps, and fuel nozzles) did not reveal any significant wear and tear. All the parts inspected were in good to excellent condition. In addition, a pump and a control from a long-term J85 engine were inspected and found in excellent shape after five years of using the additive.

Maintenance records for an Air National Guard (ANG) squadron flying F-16C and F-16D aircraft (F110-GE-100 engines) were reviewed for a year prior to the introduction of +100 fuel additive and for a year afterward. No evidence was found that the additive caused any change in the flight abort rate or was a reason for flight aborts. A similar study was conducted at a second ANG squadron, flying A-10 and OA-10 aircraft (TF34-GE-100 engines), over a similar time period, with a similar result. A pump and control from one of the high-time (440 hours) TF34 engines were inspected and found to be in excellent condition.

Corrosion and erosion tests were conducted in the GEAE BECON rigs, in the Evendale Building 703 Laboratories, to assess the effects of the additive on hot-section materials. The rigs were run at two outlet temperature levels, with a different suite of five materials tested at each level. The higher level of gas temperature was 1135°C (2075°F), and the materials tested were Inconel 718, Hastalloy X with thermal-barrier coating (TBC), Haynes 188, Advanced Material 1 with Codep coating, and Advanced Material 2. The lower temperature level was 945.5°C (1734°F), and the materials tested were Inconel 718, Hastalloy X with TBC, L605, Waspaloy, and Incoloy 909. Uncoated Hastalloy X samples were used in both tests as tares. The following +100 candidate additives were evaluated: A, C, D, B-1, B-2, and B-3 (AFRL/PRTG designations). The baseline was untreated fuel. The D additive had the lowest rate of erosion. It was followed by the A additive, C additive, B-3, B-2, and then B-1. This input was one of several which drove the additive down selection. The additive selected by the Air Force was BetzDearborn SPEC AID 8Q462. Development work has continued on several of the formulations by the respective owners. As of this writing, no second additive has been selected.

Basic fuel thermal stability testing was done using fuels supplied by the Air Force. The effects of fuel thermal stability on fouling rate (carbon initiation and buildup) were demonstrated in a small-scale rig that simulated heating the fuel in an engine fuel nozzle. Fouling rate was assessed by measuring the fuel-circuit pressure drop change as a function of time as the test ran. It was demonstrated that 15°F decrease in fuel thermal stability increased fouling rates exponentially; a 10°F decrease would increase the fouling rate by 3 times, and a 30°F decrease would increase fouling rate almost 20 times. The fuel nozzle tip temperatures simulated in these tests were selected from ANSYS analysis of F110 engine fuel nozzle models by Parker Aerospace. Use of the +100 additive in the fuel demonstrated a significant reduction in fouling rate for the worst fuels.

3.0 Technical Programs

3.1 Introduction

The use of fuel as a heat sink for aircraft subsystems is limited by the thermal stability of the fuel. To extend the thermal stability of JP-8, the Air Force has developed an additive that contains a dispersant and a detergent as main ingredients. This additive increases the limiting thermal-stability temperature of the fuel by approximately 100°F (56°C). This stability improvement will allow the fuel to be used in the advanced F-22 aircraft to cool additional components such as avionics, hydraulic oils, and weapons system computers.

The overall objective of this program was to gain approval of this additive for use in GEAE and CFMI engines. There were also a number of secondary objectives such as evaluating the effects of the additive on maintenance and overhaul aspects of the engines, testing on an advanced demonstrator engine, working with the Navy Fuels and Lubricants Directorate to obtain enough data for Navy acceptance of the additive, quantifying hot-section response to the presence of the addtive in the fuel, and upgrading a test facility, at Wright-Patterson Air Force Base, in which a demonstration of the cooled-cooling-air/fuel-heat-sink capability of JP-8+100 could be demonstrated.

The achievement of these objectives is discussed in this report. The technical effort of this program extended over five calendar years. The fuel used throughout was JP-8; the additive(s), known as "+100," were supplied through the Air Force from the additive manufacturers, who were vying for product approval. Tests were done to assess the hot-section materials corrosion and erosion effects of the additives. Military engine endurance tests were done to assess the operability and maintainability effects of the preferred additive, and a study was done at two Air National Guard bases to track maintenance actions prior to the introduction of the additive and for a year after the additive was put into service, to back up the engine testing. The preferred additive was BetzDearborn SPEC AID 8Q462. Test rig hardware was designed, manufactured, and delivered to the test cell. An extensive thermal stability study was carried out, using several fuels supplied by the Air Force. Southwest Research Institute (SwRI) of San Antonio, Texas was commissioned to do a large portion of this work. There were also a number of contributing studies to evaluate component combustor performance after engine endurance testing, assess the effects of the additive on fuel energy content, and see if there was any sudden change in benefit for a flying group who were using the additive and suddenly stopped using it.

The work was broken down into "tasks," and the tasks are reported in numerical order in the following subsections.

3.2 Task 3.1: Toxicity and Environmental Health and Safety (EHS) Review

(Deleted – See Full Report)

3.3 Engine Endurance Testing

3.3.1 Task 3.2: F110-GE-129

The first engine endurance test was on an F110-GE-129. This is an augmented turbofan with a three-stage fan, nine-stage compressor, annular combustor, single-stage high-pressure turbine (HPT), two-stage low pressure turbine (LPT), and an augmentor system. The engine is nominally rated at 29,000 lbf of thrust.

The -129 selected to run with JP-8+100 was being used for combustor CIP (component improvement program) work. The engine, ESN (engine serial number) 538103/5, was installed in sea-level Cell 38, Building 500, Evendale, Ohio, about December 3, 1996. The engine was fueled from a 125,000-gallon storage tank. The BetzDearborn SPEC AID 8Q462 (+100) material was added to the fuel, at a treat rate of 108 ml per 100 gallons of fuel (a concentration of 256 mg per liter). The fuel was pumped from tank trucks into the storage tank. The additive entered the fuel by gravity-entrainment dispersion, no injector required. Testing started on December 10. Sea-level testing was completed in June and included cyclic endurance, performance calibrations, and low-cycle fatigue. The engine was then partially torn down and inspected.

After the engine was reassembled, it was installed in Cell 43. Altitude endurance testing started on August 20. The engine effectively completed altitude endurance on October 31.

The sea-level testing comprised:

- Total run time (hours): 626.4

The altitude testing comprised:

- Total run time (hours): 164.9

The engine was disassembled, and dirty inspection was completed in March 1998. The combustor did not exceed any service limits except for wear on the aft outer seal surface. The combustor and fuel nozzles will be returned to service.

The fuel nozzles had some unusual carboneous deposits in the external boattail cone. When they were scraped and analyzed, the material was identified as chromium phosphate. Some very slight surface corrosion was associated with these deposits, but it was not consequential. This was the only factory endurance engine test in which a coating on the face of the fuel nozzles was observed.

Three and a half barrels of additive were run through the engine. Total fuel consumed from December 1996 to the end of October 1997 was 842,292 gallons. The engine had been expected to consume a total of 1.0 to 1.2 million gallons, but total afterburner testing was below expectation.

The clean layout inspection occurred in June 1998. The controls and fuel pumps for this engine were inspected at the vendors. The controls were bench tested, then torn down and inspected. The results are shown in Figures 1 through 5 for the main engine control, the augmentor fuel control, the main fuel pump, the augmentor fuel pump, and the boost pump, respectively.

The following report was provided by Hamilton Standard documenting inspection of the augmentor fuel control:

> Augmentor fuel control P/N 1459M17G06AA, S/N GAT1G005 was returned to Hamilton Standard for examination following 791 hours of operation on F110-GE-129 engine 538103 build 5C, using JP-8+100 fuel.
>
> The objective of this examination is to determine the control functional and physical condition following the engine test. The results are as follows:
>
> **Functional -** The control was subjected to an "as received" repeat of the standard production acceptance test (ATP), and the results were compared to test data taken prior to the engine test. This comparison revealed some small changes in measured parameters between pre- and posttest ATP data; however, all were within the "new part limits."
>
> The only anomaly found was the inability to properly initiate the 'PON' (augmentor fuel pump turn-on/turn-off signal) pressure due to a badly damaged electrical connector (shell deformed inward and the contact pin location distorted) on the solenoid valve that controls this fuel pressure signal. This damage was obviously the result of shipping and/or handling prior to receipt at Hamilton Standard (vendor) as no inability to operate in-augmentor while installed on engine 538103/5 has been reported. Subsequent investigation of the solenoid valve indicated that normal operation of this feature would most likely have been possible if the electrical wiring to the solenoid had been 'hay wired/jury rigged' in lieu of the test stand required cable-mating connector wiring.
>
> **Physical -** The Control was disassembled and examined for any indication(s) of any distress/anomalies that would be attributable to the exposure to and/or operation with JP-8+100 fuel. As this specific use for this control was not known at the time of its assembly, no piece-part 'as built' dimensional was obtained/recorded.
>
> Review of the disassembled hardware did not show any indication of distress, wear, or signs of impending failure. The general condition was observed as 'much cleaner than expected' for the hours of operation reported.
>
> Color photographs of internalpiece parts considered more 'key' to proper functional operation of the control were taken and are retained and available for examination by request to Design Engineering.
>
> **Conclusion -** Based on the posttest engine ATP results and physical examination of the hardware from this control, there are no known impediments to any future operation on the JP-8+100 fuel. The production combustor, clean, had some visual cracking of the skirts but was recommended for minor repair and return to engine testing.

Following engine ESN 538103, it was planned to run the next endurance engine on the additive. However, due to delayed communication, that engine test (ESN 509716) was started without additive in the fuel; in later runs the additive was introduced to the fuel, as described below.

P/N: 1534M52P14
S/N: WYG78730

Run Times for Build 5:
Component Engine Operating Time (EOT): 792 Hours
Total Run Time (TRT): 792 Hours
Engine Run Time (ERT): 716 Hours

Total run time including this block of testing is 3043 Hours EOT

Observations: The MEC was found to be in generally excellent condition. It was very clean internally. Seals, O-rings, wear surfaces, and bearings exhibited no unusual wear or distress. No safety issues or early removal for cause were identified.

Disposition/Recommendation: Recommend that the MEC can be run for additional blocks of testing.
Note: Elastomers are normally replaced during reassembly

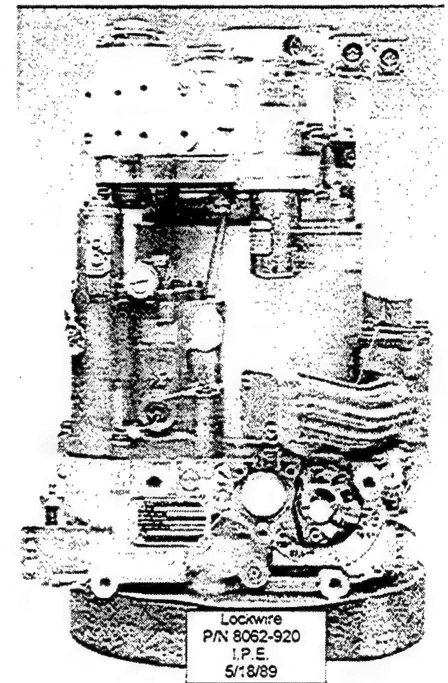


Figure 1 ESN 538103/5, 5A, 5B, and 5C Clean Layout Results: Main Engine Control

P/N: 1459M17G06
S/N: GAT1G005

Run Time: 791 Hours ERT

Observations: Posttest component within acceptance test procedure (ATP) limits. Handling damage to A/B on/off solenoid connector precluded testing of that function. Disassembly of control revealed "very clean" piece parts.

Disposition/Recommendation: Reassemble with new solenoid and use for acceptance test. No restrictions on additional engine tests.

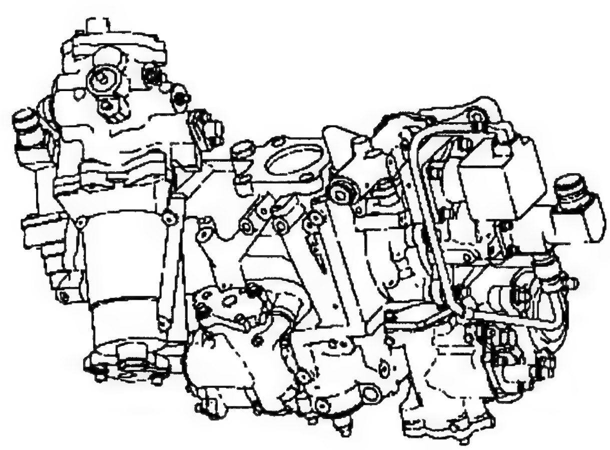


Figure 2. ESN 538103/5, 5A, 5B, and 5C Clean Layout Results: Augmentor Fuel Control

P/N: 1457M13P03
S/N: SUS0C114
Run Time: 791 Hours ERT on JP-8+100

Observations:

- No deterioration in performance.
- All elastomers in excellent condition.
- All parts in excellent condition except:
    1. Wear on filter bypass poppet seat not associated with JP-8+100.
    2. Impending bypass indicator would reset — not exposed to fuel.

Disposition/Recommendations:

- Reassemble pump. Return to Engineering Stores or engine operation.
- JP-8+100 fuel acceptance for Main Fuel Pump

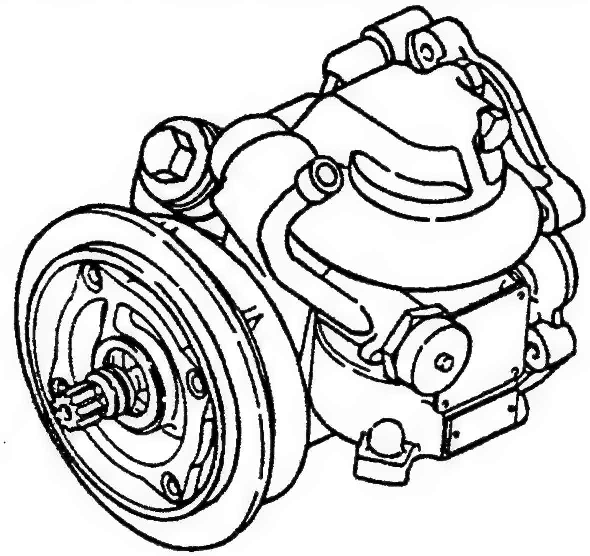


Figure 3. ESN 538103/5, 5A, 5B, and 5C Clean Layout Results: Main Fuel Pump

P/N: 9338M20P07
S/N: SUS2049F
Run Time: 791 Hours ERT on JP-8+100

Observations:

- No deterioration in performance.
- All elastomers in excellent condition.
- All parts in excellent condition except inlet valve piston and stem damaged during disassembly.

Disposition/Recommendation:

- Reassemble pump and return to Engineering Stor
or engine operation.
- JP-8+100 fuel is acceptable for augmentor fuel pu

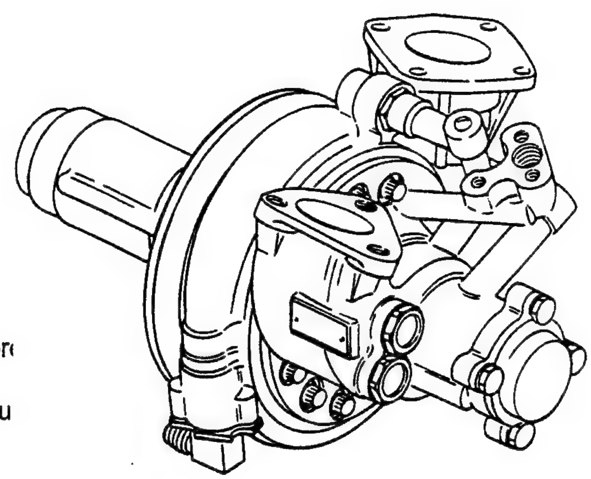


Figure 4. ESN 538103/5, 5A, 5B, and 5C Clean Layout Results: Augmentor Fuel Pump

P/N: 1296M72P01
S/N: LJA33125
Run Time: 791 Hours ERT
Teardown is complete. All internal components are in excellent condition. There are indications of cavitation on "C" element blade tips, liner, and adjacent bearings.

Observations:

- Wear measurements complete. All parts within T.O. limits.
- No degradation of elastomeric seals due to exposure to JP-8+100 fuel.
- One carbon seal broken during disassembly. No abnormal wear patterns observed.

Disposition/Recommendations:

- Rebuild pump and return to Engineering Stores.
- Fuel boost pump OK to use with JP-8+100 fuel.

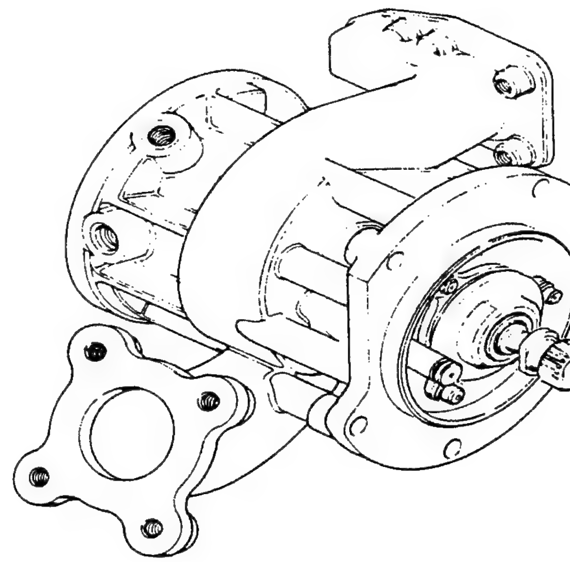


Figure 5 ESN 538103/5, 5A, 5B, and 5C Clean Layout Results: Fuel Boost Pump

3.3.2 Task 3.3.1: F110-GE-100

F110-GE-100 engine ESN 509716/6A ran 587 sea-level cycles, and 156 of 197 ram cycles in the altitude cell. The engine consumed 177,786 gallons of JP-8 and 340,380 gallons of JP-8+100. The engine was disassembled to modules and held for dirty inspection. This engine ran about 67% of the time on +100 fuel. There was no attempt to inspect, in detail, the controls and pumps, because other F110-100 engines in the fleet have more time on the fuel and have had no problems.

3.3.3 Task 3.3.2: F110-GE-400

The Navy requested an accelerated simulated-mission endurance test (ASMET) using the additive. F110-GE-400 ESN 588109/6 was selected, ran power calibration, and then completed a planned 780-cycle ASMET test, all on JP-8+100. The endurance test ran for a total of nearly 697 hours, all at sea level conditions. Totals from the test were:

- Total run time (hours:minutes): 772:46
- Total endurance time (hours:minutes): 696:50

The engine was sent to Tinker Air Force Base for teardown and inspection. Dirty layout was satisfactorily completed. The controls and pumps were inspected in detail, because (1) an F110-129 control was being certified on the engine and (2) the pump, an Argo-Tech, was a model type that had never been inspected. The layout results are shown in Figures 6 through 16 and described below. Clean inspection was done on May 16 and 17, 1999, with the following results.

Figure 6 Main Fuel Control, Dirty Layout *ESN 488109/6 - Parts look very clean.*

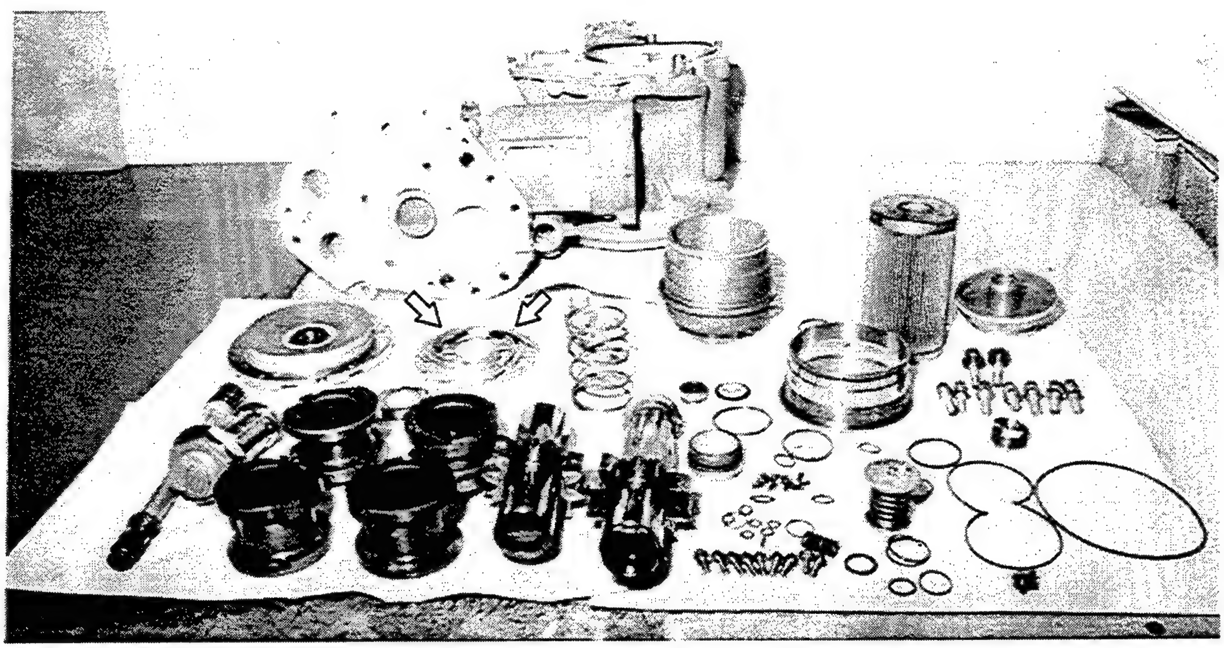


Figure 7 Main Fuel Pump, Dirty Layout *ESN488109/6 - Note chunks of rubber in impeller.*

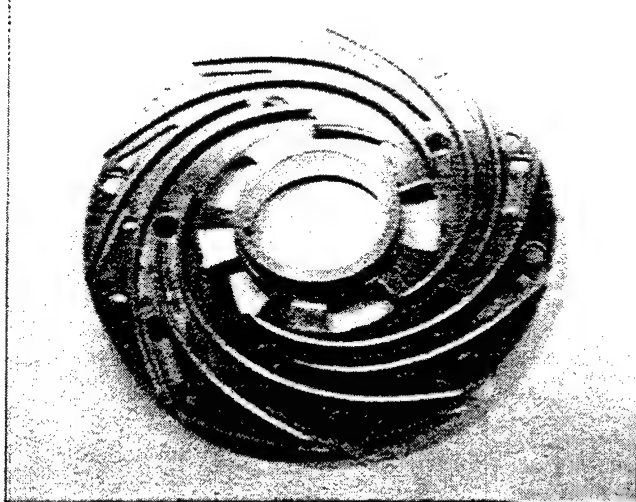


Figure 8. Impeller with Rubber Chunks Removed

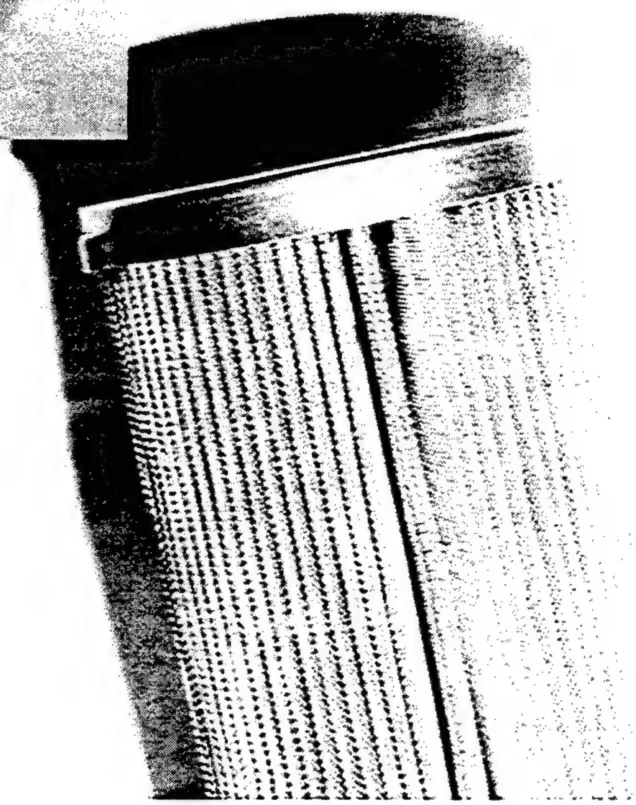


Figure 9. Filter Element, Main Fuel Pump

Note faint cavitation marks on gear spline.

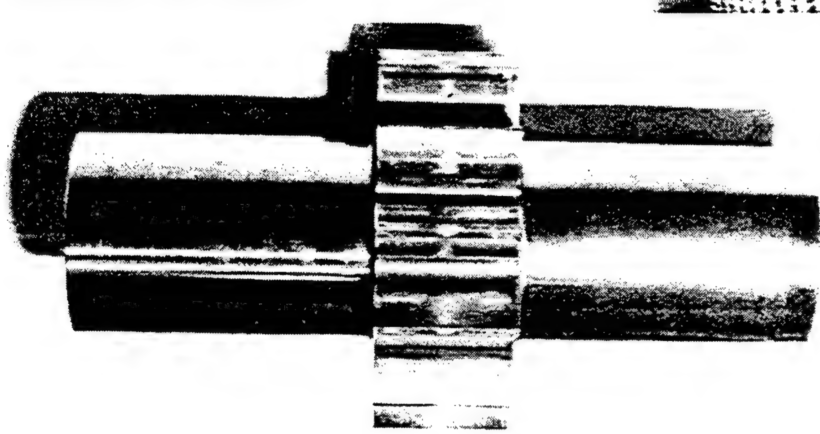


Figure 10. Gear Element, Main Fuel Pump

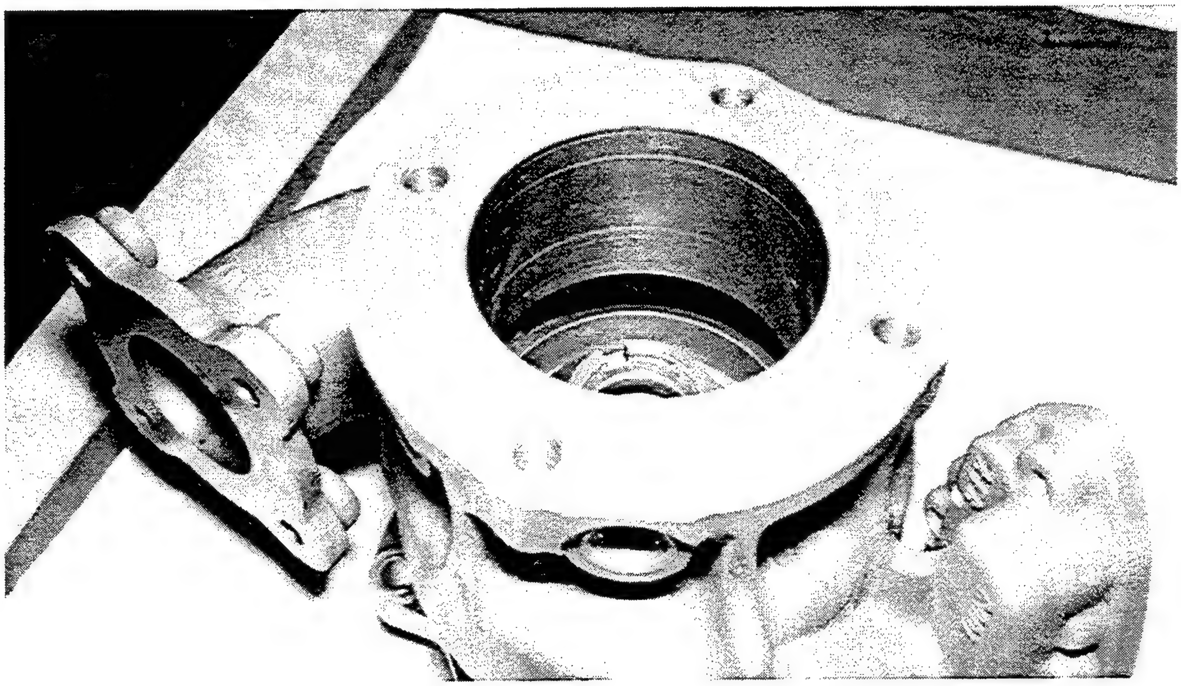


Figure 11. Fuel Boost Pump Housing, Dirty Layout *ESN 488109/6*

Figure 12. Impeller, Fuel Boost Pump

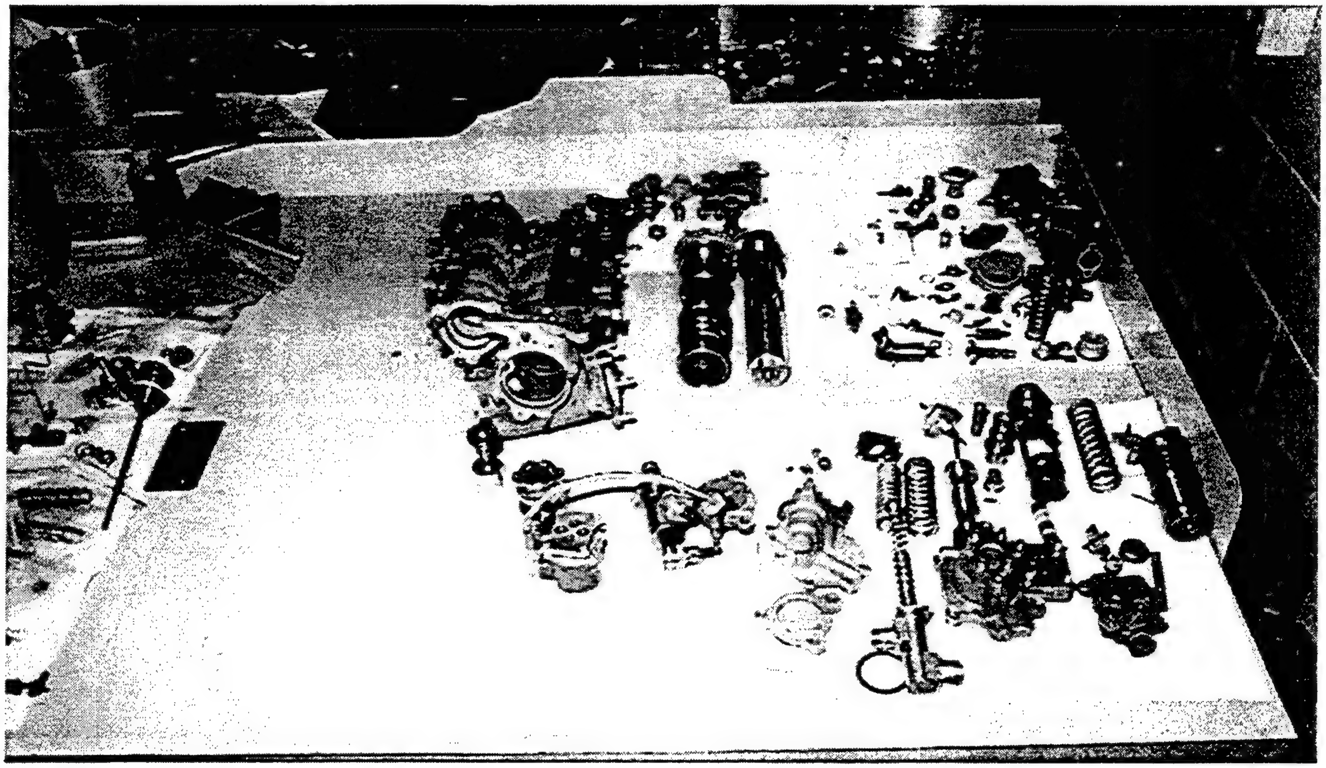


Figure 13. Augmentor Fuel Control, Dirty Layout *ESN 488109/6*

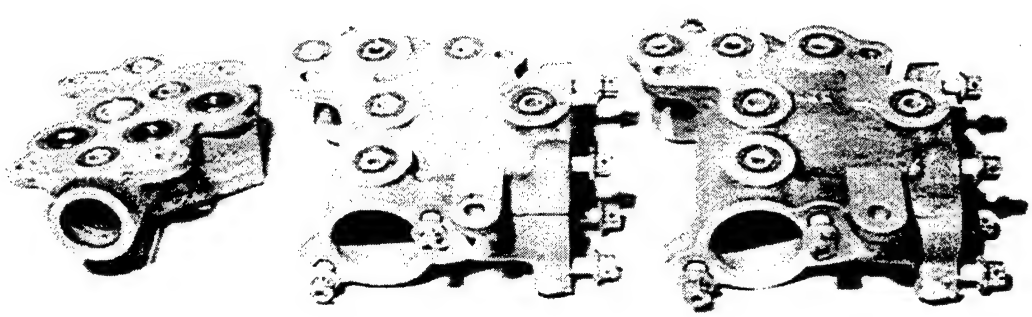


Figure 14. Housing Attachments, Augmentor Fuel Control

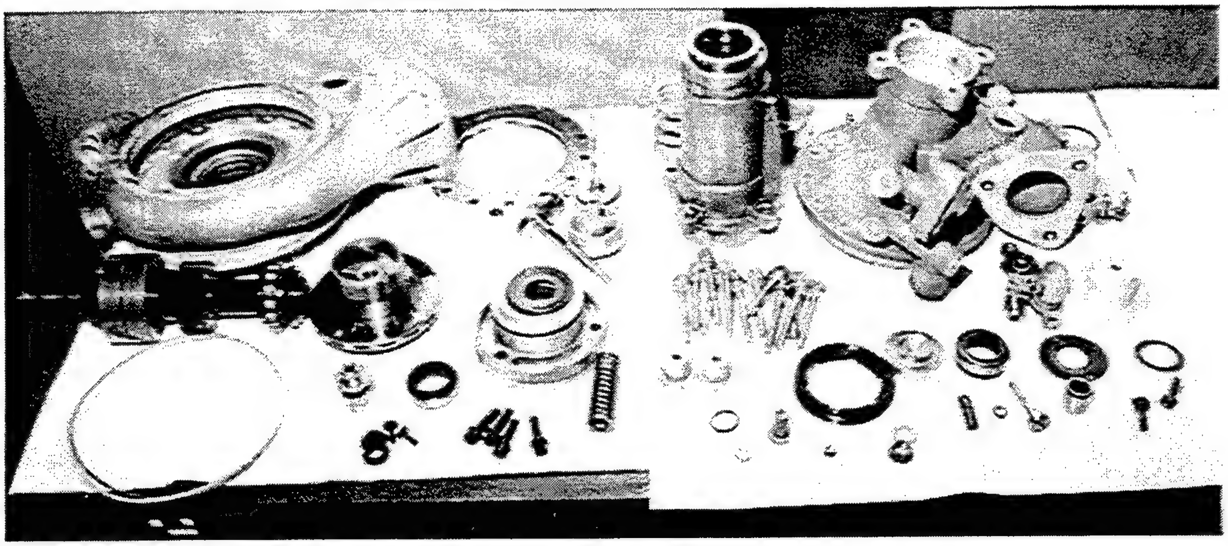
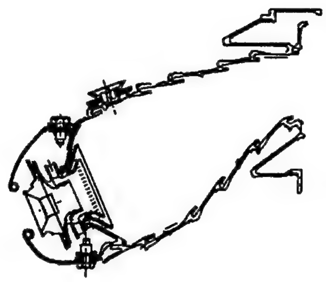
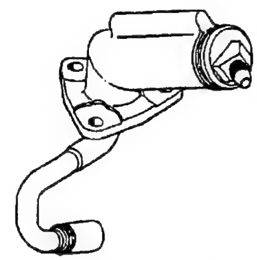


Figure 15. Augmentor Fuel Pump, Dirty Layout ESN 488109/6

Figure 16 Typical O-Ring from Augmentor Fuel Pump *Little wear evident.*



Combustor - Engine operating time (EOT) at teardown was about 773 hours. The dome was in generally excellent condition. Swirlers and venturis were also in excellent shape. The outer skirt was in excellent condition; only nine cracks were observed — none longer than 3/4 of a panel. The inner skirt was in good condition with no burned holes, and no circumferential cracks. Minor dents were observed on the outer cowl; the inner cowl was in excellent shape. *Repair and return to service* was recommended for the dome, cowls, and outer skirt; *repair or replace* was recommended for the inner skirt.



Fuel Nozzle - EOT at teardown was about 773 hours. All fuel nozzles passed flow check; two were out of limits on the pressure-decay test. All nozzles had some tip wear; one had heavy wear (maybe out of limits). Most nozzles had some tip carbon — more than expected but not untypical. *Repair and return to service* was recommended.

Main Engine Control (MEC) - EOT at teardown was about 3699 hours. Internal and external leakage were within limits. Hardware was in very good condition overall. Normal handling damage was evident on external surfaces. Seals showed set expected for the operating time. The carbon bearings were in very good condition. Gears and bearings were serviceable. There were no hardware issues related to JP-8+100.

Main Fuel Pump - EOT at teardown was about 3010 hours. The overall condition was good. O-rings and seals were in very good condition (no distress); minor set was seen in some seals. Observed gear and bearing wear/cavitation and housing rubs were considered normal. Part No. 1973M67P08 (F110-129 Argo-Tech pump), which was new to the engine, was inspected to permit qualification of the fan engine.

Fuel Boost Pump - EOT at teardown was about 4036 hours. Overall condition was very good. Carbon seals and O-rings were in very good condition; there were minor chips on one carbon seal and minor set on the O-rings. The thrust bearings, impeller, and housing were in excellent condition.

Augmentor Fuel Pump - Prior to the JP-8+100 test, there was a shop visit at 1869 hours EOT (workscope unknown). EOT at teardown was about 3386 hours. Leakage was zero, although leakage has been experienced with similar pumps. Wear appeared normal. Carbon seals and O-rings were consistent with similar pumps. The inlet-valve housing showed sealing surface wear, and the Teflon seal was worn. The carbon oil seal showed heavy deposits, but the sealing surfaces were good. The discharge-valve O-ring exhibited significant set, and minor cavitation was evident on the impeller and housing.

Augmentor Fuel Control - Prior to the JP-8+100 test, there was a shop visit at 2328 hours EOT to fix leakage at the bellows assembly; some O-rings were replaced. EOT at teardown was about 14,226 hours. The control was in excellent condition. The O-rings replaced during the shop visit were in very good condition; the original O-rings showed more set. All other components were in very good condition with no distress noted.

3.3.4 Task 3.3.3: TF39

TF39 CIP ESN 441587/3 engine test was started on February 22, 1999 and completed 1000 "C" cycles (accelerated service cycles) on JP-8+100. The engine was moved to Kelly Air Force Base where it was torn down, and major hot-section parts were laid out for dirty inspection. These inspections were made in the first half of January 2000. The engine was then loosely reassembled and stored. Parts will be refurbished prior to the next test, once the engine test mission has been established. JP-8+100 was used through all 1000 C cycles.

Results of the dirty layout inspection were as follows.

Combustor - The combustor was in excellent shape. Time since new was 322.8 hours in a prior build and 300^{+} hours in this engine test. The cowl, rivet joints, fuel nozzle, and ignitor eyelets had no discrepancies. Mounting pin bushings had no discrepancies. The dome had no cracks, no panel overhang distortion, no burn-through, and no ignitor ferrule distortion. All the venturi swirlers, retainers, and antirotation tabs were in very good condition.

Swirler discharge surfaces were in excellent shape. The cup six flare cone had some minor nibbling at the upper left corner (aft looking forward); this was the only damage noted. Liner seals were in excellent shape with no cracks or distortion. Neither liner had any circumferential cracks. There was some minor overhang trailing-edge nibbling on the outer liner, but there was no burn-through on either liner. The inner liner had six axial cracks on panel one. The outer liner had three axial cracks on the first panel; and three axial cracks in panel 9, nothing longer than a panel length. Disposition was *wash and repair, return to service.* Engine fuel nozzles were in excellent shape. Nozzles were clean and flowed more after the test (+1.01 %). Nozzles were exercised and reflowed. They were still over by a fraction of a percent.

Fuel Pump and Control - The engine fuel pump and control are awaiting removal for teardown inspection. No word if parts will be inspected, as yet.

Turbines - The engine turbine section was inspected. HPT turbine stators were in good shape, as were the rotor and blades. LPT stage 1 was colored purple and had some coating loss but was generally in good shape. The turbine rear frame was in good shape, as were the rotor and blades.

3.3.5 Associated Engine Test Topics

3.3.5.1 Fuel Storage Tank Dirt

The initial plan was to fuel the engines from a 125,000-gallon storage tank. The additive was to be put in, as the fuel was pumped from tank trucks into the storage tank, by gravity-entrainment dispersion (no injector required). The storage tank had been cleaned within the past 12 months, but there was concern about how much debris the additive would "clean" off the walls of the tank and from the fuel lines to the cell. There was also considerable discussion on the water-separator filters and when they should be replaced after introduction of the additive. It was decided to monitor pressure drop through the filter (ΔP) and to replace it if ΔP reached 25 psi. GEAE had two sets of special Aquacon filters on hand.

It was noted that this introduction of the additive into a "virgin" system could provide the Air Force with a considerable amount of data on how a system reacts to the additive, and GEAE was asked to keep detailed records on the subsequent start-up events. At the end of the test, the fuels personnel reported that the filter ΔP went up to 3 psi, from 0 at the start of the test, and reached that level at a point in the test when it would still be expected to be zero. Thus, the additive did appear to induce scale accumulation in the filter. However, the ΔP did not further increase. The conclusion is that if +100 is added to fuel going into a system already in continual use, then the detergent action of the additive on the tank and fuel-transport piping need not cause concern.

3.3.5.2 Fuel Heating Value with the Additive

Due to hot-section damage experienced on the –129 and –100 engine tests, GEAE Engineering asked if the addition of +100 at 256 ppm significantly increased fuel heating value. Data samples of fuel heating value from four fuels tested neat and with the additive, supplied by the Air Force, with the calculation being done by Pratt & Whitney, did indeed show increased fuel heat content with the additive. Data from BetzDearborn show the heating value of the additive itself (18,360 Btu/lbm) is slightly below the lower heating value of the fuel (18,400 Btu/lbm) and the heat of vaporization of the additive is higher than that of the fuel (409 and 369 J/g, respectively). However, BetzDearborn also reported that, while the gross heat of fuel without the additive is higher than with it, the net heat values are higher with the additive. Further data were collected and are presented in Table 1.

Table 1 Comparison of Net Heat of Combustion, JP-8 With and Without +100 Additive

Fuel Sample Source/Designation	Heat of Combustion, Btu/lbm	
	Neat	With Additive
POSF (Burlington,VT) 3220/3229	18,551	18,627
POSF (Otis, MA) 3232/3233	18,606	18628
POSF (Barnes, MA) 3234/3235	18,622	18,629
POSF (Sheppard AFB)	18,619	18,662
POSF-3166 (Feb. 1998) at WPAFB	18,616	Not tested
POSF-3166 (Dec 1998) at BetzDearborn	19,630* Gross	19,620 Gross
ReTest (Jan. 1999) at BetzDearborn	19,487 Gross	19,473 Gross
POSF-3166 (Jan. 1999) at SwRI	19,830 Gross	19,847 Gross
POSF-3166 (Jan. 1999) at SwRI	18,574	18,578
GEAE Fuel Farm, Feb. 1999	18,551**	18,577
GEAE Fuel Farm, Feb. 1999 (2nd Set)	18,562	18,582
* Does not account for lost latent heat of water. ** Repeatability of Method is 22 Btu/lbm, annotated by laboratory technician.		

The net heat of combustion accounts for heat loss due to noncondensing water vapor in the fuel as gases leave the combustion chamber. Net heat with the additive is higher in every comparison done. In two instances, net heat with the additive is higher than the neat value plus the repeatability value. If the fuel heating value were greater with the additive, then for a given throttle position, the engine control would have only scheduled as much fuel flow as necessary to reach the required mechanical rotor speed. This makes overheating of the turbine parts less likely. In the case of the gross heats, where no corrections were done, two of the three show that the gross heat was lowered by the additive. This is believed to be the actual trend. In any event, the changes in fuel heating value are well less than 1.0% of the overall heating value.

3.3.5.3 Combustor Component Test

As part of the Engine 538103/5A turbine damage investigation, full-annular component tests were run on both the combustors that were used in this engine. The purpose of these tests was to measure the combustor discharge gas temperature uniformity and compare the average radial temperature profile (important for rotating parts life) and the peak hot-spot temperature, or pattern factor (important for static parts life), to the design requirements. Both combustors were tested using JP-8 and JP-8+100 fuel; the results are presented in Table 2. There was no combustor performance difference due to the fuel type tested.

Table 2 Combustor Atmospheric Test Performance

Combustor	Fuel	Profile Peak		Pattern Factor	
		Max. Allowable	Test Result	Max. Allowable	Test Result
Combustor 1	JP-8	1.10	1.11	0.25	0.34
	JP-8+100		1.11		0.35
Combustor 2	JP-8		1.09		0.22
	JP-8+100		1.09		0.23

3.3.6 Conclusions from Engine Tests

Four endurance engines were run on the additive. Two engines came through the testing with no damage to the hardware except fair wear and tear. The third engine suffered failure of a turbine blade that already had undergone significant endurance testing and might have been considered to be at the end of a reasonable life. Further, that failure was not the usual mode.

The fourth engine was removed from the cell, with shroud wear damage, very near the end of the test program. This engine ran on a combination of neat fuel and +100 fuel. The shroud damage was not untypical in these engines.

All the hot-section components were in, otherwise, very serviceable condition. Inspection of pumps and controls suggested only normal fair wear and tear. There were no anomalies. The conclusion was that the additive places no significant burden on engine operation.

3.4 Task 3.4: Spraybar Coke Reduction Tests

This planned task was not implemented.

3.5 Task 3.5: Base Maintenance Record, Field Experience Survey

Southwest Research Institute evaluated the effects of JP-8+100 on the maintenance and operations of TF34-GE-100 and F110-GE-100 engines. The following subsections are adapted from the reports prepared for GEAE by SwRI.

3.5.1 TF34-GE-100

The purpose of this project was to determine the effect of using JP-8+100 fuel on the maintenance and operation of the T34-GE-100 aircraft engines used on the A-10 aircraft. A field demonstration had been established by personnel from the Air Force Fuels Branch (AFRL/PRTG) with the 104th Fighter Group (FG) of the Air National Guard located at the Barnes ANG Base in Westfield, MA.

SwRI, under subcontract to GEAE, had the responsibility to collect and evaluate the maintenance data on the test aircraft; abort data were also collected because they reflect operational problems and relate to maintenance activity. The information was provided on a monthly basis to SwRI by maintenance and logistics personnel of the 104th FG. As part of the evaluation, visits were made to the engine maintenance unit of the 104th FG to review the results and verify the conclusions; these visits were made once a quarter and again at the end of the evaluation period. SwRI personnel were able to visually inspect one of the test engines while it was torn down for a 500-hour inspection.

The evaluation period was 14 months, from the beginning of April 1996 through May 1997. A historical evaluation was also made by collecting data on flight aborts and unscheduled maintenance for the selected engine items for the 21-month period that the 104th FG flew on JP-8 prior to the JP-8+100 evaluation period.

The maintenance evaluation was conducted on components of the airframe, engine fuel systems, and hot-section considered likely to be affected by the fuel change; these components were selected by GEAE. Only components replaced during unscheduled maintenance were considered for analysis.

Data on the number of aborts and their causes were obtained from the 104th FG Logistics Group (104 LGM). Engine operating time (EOT) was also obtained from the 104 LGM. Engine hours were adjusted when test aircraft were deployed from home base to locations where JP-8+100 was not available and they flew on JP-8. The JP-8 hours were not counted. This subsection reports the maintenance and abort data collected by SwRI and evaluation of that data.

3.5.1.1 Field Demonstration Program

A coordination meeting was held at the 104th Fighter Group, March 1996, to initiate the field demonstration program. Representatives from the 104th FG, AFRL/PRTG, the San Antonio Air Logistics Center (SA-ALC), and SwRI attended the meeting. The TF34 Engine Manager from SA-ALC/LPEBE, Mr. Tim Lawless, presented the test

plan developed by his organization. Authorization to use JP-8+100 was granted by the SA-ALC/LPEBE on March 19, 1996. Eight of the seventeen aircraft assigned to the 104th FG were designated as test aircraft; the remaining nine aircraft were designated as control aircraft and continued using untreated JP-8 fuel.

Aircraft Description

The test aircraft used for the demonstration were A-10 *Thunderbolt II* "Warthogs," each powered by two T34-GE-100 turbofans. Table 3 lists the aircraft tail numbers, serial numbers of installed engines at the start of test, and the date these aircraft began the demonstration program.

Table 3 Identification of Test Aircraft and Engines

Aircraft Tail Number	Engine 1	Engine 2	Program Start Date
780583	205606	205891	20 March 1996
780614	205045	205568	20 March 1996
780626	205284	206015	20 March 1996
780628	205630	205539	20 March 1996
780630	205658	205535	02 April 1996
780647	205608	205585	19 March 1996
790104	205699	205571	25 April 1996
800166	205548	205932	05 April 1996

Data Collection

A copy of the Technical Order for the A-10 and copies of the work unit codes (WUC) were provided to GEAE to identify fuel and hot-section components to be tracked on the test aircraft. Table 4 identifies components (and the WUC's) selected by GEAE for tracking.

Meetings were held with data-processing and engine maintenance personnel to determine which database(s) would provide the best results for the data being requested. The two databases discussed were the Consolidated Engine Management System (CEMS) and the Core Automated Maintenance System (CAMS). Unit personnel collectively agreed that the CAMS database would yield the best results tracking above-mentioned WUC's.

Data were requested on the test aircraft from July 1994, when the unit began using JP-8, through March 1996 and from April 1996, when the test aircraft were converted to JP-8+100, through May 1997, when this demonstration program terminated. Only components replaced during unscheduled maintenance actions were considered for analysis. In addition to tracked component replacements, data on air and ground aborts were provided from January 1, 1995 through May 30, 1997. The Logistics Group of the 104th FG provided the engine operating hours for test and control aircraft from July 1994 through September 30, 1997 to enable calculations of abort rates before and during JP-8+100.

Maintenance costs were determined on the basis of the cost of the component and the standard labor requirement for that action.

3.5.1.2 Data Evaluation

Three sets of data are discussed: (1) engine/airframe hours, (2) unscheduled maintenance actions on tracked items, and (3) aborts.

Table 4 Component Work Unit Codes Tracked at the 104th FG

WCU	Component	WCU	Component
23AK0	Engine Exhaust System	23CCS	Exhaust Frame
23CL0	Combustion Section	23DCA	Main Fuel Control (TCI)
23CLE	HPT Nozzle Assy, Stage 1	23DCF	Main Fuel Pump
23CLL	Combustion Liner	23DCJ	Main Fuel Filter
23CM0	HPT Rotor Assy (TCI)	23DCL	Main Fuel Filter Element
23CME	Turbine Disk, Stage 1 (TCI)	23DDF	Fuel Distributor
23CMF	Turbine Blade, Stage 2 (TCI)	23DDG	Fuel Distributor Filter Barrier
23CMK	Turbine Disk, Stage 2	23DDH	Valve, Fuel Check
23CMF	Turbine Blade, Stage 2(TCI)	23DEA	Fuel Injectors (Exc. No. 13)
23CMR	Blade Set, Stage 1 Turbine	23DEB	Fuel Injector, No.13
23CMT	Blade Set, Stage 2 Turbine	23DF0	Fuel Primer System
23CN0	HPT Stator Assy	23DFA	Primer Shutoff Valve
23CQ0	LPT Stator Assy	23DFE	Fuel Primer Nozzles
23CQC	Turbine Shroud Sector, Stage 4	23DFH	Primer Drain Valve
23CQD	Turbine Shroud Sector, Stage 5	23DJE	Ignitor Plug (TCI)
23CQE	Turbine Shroud Sector, Stage 6	23DLV	Oil Cooler
23CR0	LPT Rotor Assy	46EA0	Pump Assy, Main Tank Boost
23CRB	Turbine Blade, Stage 3	46EC0	Pump Assy, Wing Tank Boost
23CRS	Blade Set, Stage 3 Turbine	46ECB	Pump, AC, Boost
23CRT	Blade Set, Stage 4 Turbine	46EE0	Pump, DC, Boost
23CRU	Blade Set, Stage 5 Turbine	46EG0	Fuel Feed Control System
23CRV	Blade Set, Stage 6 Turbine		

Engine/Airframe Hours

Detailed data for flight hours of the aircraft are listed in Tables 5 through 8. Figure 18 presents separate histories of the total flight hours per month for the control and test aircraft. The dashed lines superimposed on the history graphs show the averages for each group of aircraft before and during the test period. The important thing to note is that, during the 14-month test period, the control aircraft and the test aircraft averaged almost the same number of flight hours per month.

Unscheduled Maintenance Actions on Tracked Items

There were very few unscheduled maintenance actions on the tracked items during either the test period (April 1996 to May 1997) or the historical period (July 1994 to March 1996). Of the 43 items tracked, only 8 had any unscheduled maintenance either before or during the test period.

Figure **19** is a historical summary of these actions for all aircraft. During the historical period, there were 14 unscheduled maintenance actions on the tracked items, four of which were to replace the fuel control. During the test period itself, the only unscheduled maintenance action on the tracked items reported to SwRI by the 104th FG was one replacement of a fuel control on one of the test aircraft in May 1996; other than that, there were no unscheduled maintenance actions on either set of aircraft during the test period.

Table 5 **Monthly Flight Hours for Test Aircraft Before the Test Period** *Average hours flown per month = 191.*

Aircraft No.	1995												1996			Totals
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	
78-583	18.7	8.8	4.6	29.6	49.1	62.5	7.2	0	6.3	12.2	16.2	5.1	0	28.4	22.4	271
78-614	46.7	17.5	23.4	35.5	65.8	25.8	6.4	45.1	78.0	38.0	21.1	13.8	17.6	55.3	16.6	507
78-626	0	35.9	41.1	15.4	38.1	38.6	1.8	56.8	53.7	24.1	34.7	11.9	15.1	42.7	26.5	436
78-628	14.9	24.4	31.5	43.9	20.7	14.6	7.2	33.1	38.9	16.2	25.8	0	17.9	46.5	37.3	373
78-630	19.1	26.6	9.5	9.8	0	7.0	41.3	47.6	85.8	33.1	4.0	13.5	11.6	51.6	3.4	364
78-647	31.5	31.9	2.9	16.7	3.8	0	8.1	40.7	65.4	49.2	22.7	12.2	17.4	9.1	4.5	316
79-104	12.4	4.1	17.0	21.3	17.6	9.7	0	35.1	31.9	4.0	25.5	27.4	32.2	0	0	238
80-166	28.4	39.3	41.2	6.9	4.8	0	22.7	48.8	83.1	35.6	10.5	1.8	7.0	27.2	3.5	361
Totals	172	188	171	179	200	158	95	307	443	212	160	86	119	261	114	2866

Table 6. Monthly Flight Hours for Test Aircraft During the Test Period *Average total hours flown per month = 208*

Aircraft No.	1996									1997					Totals
	A	M	J	J	A	S	O	N	D	J	F	M	A	M	
78-583	23.7	33.9	54.6	50.0	38.5	0	18.7	30.4	5.9	27.5	10.2	0.6	8.8	0	303
78-614	36.8	28.5	21.3	26.1	5.8	0	38.9	52.1	19.8	58.2	31.7	6.8	39.0	41.8	407
78-626	40.7	24.5	33.3	9.7	25.7	15.1	0	0	10.4	62.9	37.5	52.5	21.4	27.1	361
78-628	43.4	33.3	19.5	15.5	66.8	36.3	39.6	44.2	3.1	11.7	3.6	0	0	0	317
78-630	31.9	33.3	24.4	16.9	21.3	12.4	0	3.4	31.2	43.5	21.0	37.2	36.4	27.8	341
78-647	11.0	16.4	0	36.2	37.2	60.6	49.1	13.1	7.7	60.7	25.7	30.7	35.6	26.2	410
79-104	2.2	45.3	2.5	51.7	60.7	57.7	16.9	32.4	10.6	28.4	17.0	51.9	14.5	0	392
80-166	19.3	28.1	45.9	0	39.6	33.7	7.5	3.7	0	32.2	34.7	50.2	47.9	36.9	380
Totals	209	243	202	206	296	216	171	179	89	325	181	230	204	160	2910

Table 7. Monthly Flight Hours for <u>Control</u> Aircraft <u>Before</u> the Test Period *Average total hours flown per month = 265*

Aircraft No.	1995												1996			Totals
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	
78-611	22.8	30.3	30.3	43.7	37.2	23.2	46.6	4.1	0	15.4	13.4	1.6	24.6	36.6	12.0	342
78-612	10.2	11.4	33.0	17.9	60.5	48.1	4.5	32.9	49.0	24.1	17.2	10.8	12.2	40.8	18.5	391
78-616	14.5	34.4	37.6	21.9	38.2	18	18.7	33.6	55.9	45.4	9.3	42.3	18.3	0	11.7	400
78-624	30.2	29.2	15.6	20.8	0	0	0	0	0	6.8	14	13.4	30.4	17.3	0.9	179
78-632	28.5	8.6	14.2	19.7	8.2	16	47.7	44.5	9.1	44.6	17.9	6.8	13.6	44.3	22.5	346
78-640	0	0	1.7	21.8	11.9	36.9	30.3	40.2	111	38	8	16.4	5.3	18.4	20.9	361
78-642	29.4	28.4	20.1	9.9	47	13.6	0	0	0	0	8.8	24.5	25.5	37.6	23.2	268
78-644	43.4	14.3	23	2	59.1	52.7	46.6	34.3	0	0	0	0	16.4	46.8	33.8	372
78-649	14.9	38.2	0	9.6	10.6	71.9	15.3	46.2	57.7	21.2	14	6.9	20.8	31	20.1	378
78-659	2.1	14.1	34	6.9	26.7	58.9	5.8	37.1	47.5	37.1	16.5	8.6	20.6	12.6	37.4	366
78-696	38.4	44.9	22.3	0	8.2	8	40.7	20.5	77	22.5	6.5	1.1	1.5	0	0	292
80-191	15.8	9.7	17.4	26.2	0	9.7	30.9	24.1	42.1	44.3	25.2	5.1	14.4	10	5.2	280
Totals	250	264	249	200	208	357	287	318	449	299	151	138	204	295	206	3975

Table 8 **Monthly Flight Hours for Control Aircraft During the Test Period** *Average total hours flown per month = 203*

Aircraft No.	1996									1997					Totals
	A	M	J	J	A	S	O	N	D	J	F	M	A	M	
78-611	26.7	17.3	0	0	0	0	0	0	0	0	0	0	0	0	44
78-612	9.8	24.6	44.8	16.5	22.6	53.9	9.8	6.1	1.8	0	0	5.1	38	28.2	261
78-616	34.3	16.5	39.3	5.9	46.3	14.9	17.8	36.7	21.3	57.8	28.8	27	17.9	11.4	376
78-624	0	9.8	0	0	0	0	0	0	0	0	0	0	0	0	10
78-632	2	31.4	21.7	17.6	22.6	0	17.7	62.2	16.3	58	30 .4	43.1	16.8	33.4	373
78-640	27.1	27.2	13.4	0	56.6	54.4	21.3	44.4	14	11.9	26.3	11.5	25.5	26.9	361
78-642	37.1	22.1	26.2	44.1	60 .3	32.5	15.2	5.5	14.2	1.8	0	0	25.1	31.2	315
78-644	29.8	51.2	38.7	16	40 .6	64.5	31.4	0	2.3	10 .1	6.5	0 .5	9	0	30 1
78-649	31.9	41.2	26.4	14.4	0	36.3	0	0	0	0	0	1.4	40 .7	34.3	227
78-659	22.5	0	47.9	23.5	31.8	56.2	42.1	47.8	7.4	44.7	32	25.7	7.8	28.4	418
78-696	13.8	8.4	17.6	14.6	14.5	15.3	10 .1	8.6	1.8	19.9	0	0	0	16.4	141
80 -191	3.5	8.3	0	0	0	0	0	0	0	0	0	0	0	0	12
Totals	239	258	276	153	295	328	165	211	79	20 4	124	114	181	210	2838

Table 9 Summary of Causes for Aborts on Test Aircraft

Cause for Abort	1995												1996												1997				
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Engine Fuel Leak	2																												
Brakes	1																												
Anti-Ice System			1																										
Fuel Relay Switch			1																										
Computer A-D Inoperative			1																										
Sta 3 Lights	1																												
Temperature Sensor						1																							
Shorted Wire							1																						
Elevator Trim Tab									1																				
ECM Reprogramming									1																				
Battery Invertor											1																		
Hydraulic Leak												1																	
Steering													3																
HUD Inoperative													1	1						1									
Engine Generator													2												2				
Canopy Lock													1						1										
Anti-Skid Inoperative													1												1				
Fuel Leak														1															
Aim Light Malfunction														1															
INS Inoperative														1					1										
Oxygen Regulator														1															
Fan Speed Indicator														1															
APU Shutdown																	1												
Engine No Start																	1												
Main Landing Gear																	1	2		1		1							
Engine Throttle																		1											
Oil Pressure Sensor/Indicator																				2									1
Stability Aug. System Fail																				2									
Flap Inoperative																					1						1		
Engine Door Latch																					1								
Starter Control																						1							
Low Battery																							1						
Foreign Object in Cockpit																										1			
Canopy Light																												1	

Table 10 Summary of Causes of Aborts on Control Aircraft

	1995												1996												1997				
Cause of Abort	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Landing Gear	1					1							1																
Engine Pylon Hydraulic leak	1																												
Starter Control Valve	1																												
No HUD		1																	1				1	1					
Elevator Disconnect Light		1																											
FOD in Cockpit		1		1								1																	
APU No Start		1							2								1				2								
Engine Vibration					1								1	1															
Canopy Unlocked				1																					1				
Anti-Skid Failure					1										1														
Flat Tire					1												1												
Bad Relays						1																							
Low Hydraulic Pressure						1	1																	1	1				
Computer A-D Converter						1																							
Fuel Gage						1																							
Engine No Start							2		1	1	1																		
Radar System									1																				
Electronic Processing Unit									1																				
Flap Control										1																			
Missile Armament Video Card										1				1											1				1
Pitch Trim										1										1									
Aileron Hydraulic Leak											1																		
Aileron Trim Motor											2																		
Hydraulic Accumulator													1								2								
Canopy Actuator													1																
Canopy Lock Light													1																
Hydraulic Leak														1									1	1					

Table 10. Summary of Causes of Aborts on Control Aircraft (Concluded)

Cause of Abort	1995												1996												1997				
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Engine Oil Leak														1			1											1	
Annunciator Panel														1															
Control Display Unit														1															
Gun System														1															
ADI Fluctuating														1															
Throttle Warning Switch															1														
Air Leak															1														
Engine Fluctuation																1													
VTR																1													
Cockpit Noise/Smells																1							1					1	
Engine Oil Fluctuation																	1												
Altimeter																		1											
Radio																		1											
Bird Strike																			1										
Engine Generator																				1		1				1			
APU Fire Loop																				1									
Fuel Totalizer Erratic																				1									
APU Bleed Air Light																				1									
Aircraft Fuel Leak																									1	1			
Hung Bomb Indicator																									1				
Air Speed Indicator																										1			
Engine Fuel Flow Gage Erratic																												1	
Flap Edge Cover Cracked																												1	
Battery Inverter																												1	
Lateral Trim Inoperative																													1
FOD in Gun Bay																													1

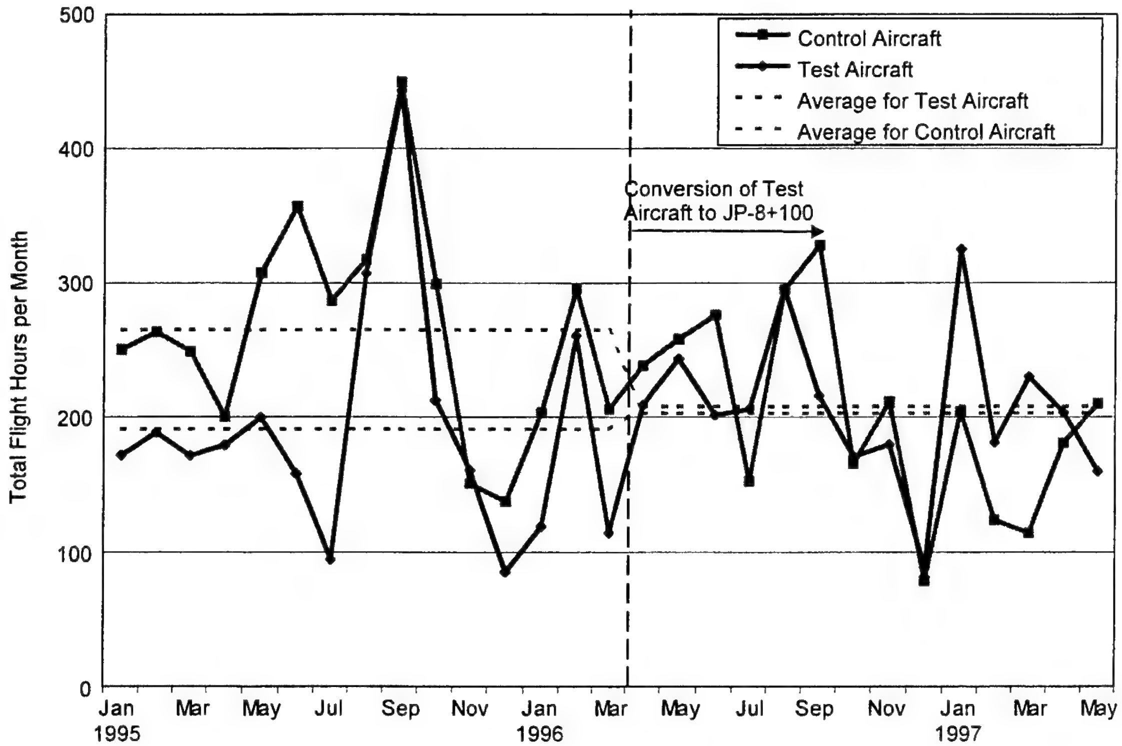


Figure 18 Summary of Monthly Flight Hours for Test and Control Aircraft

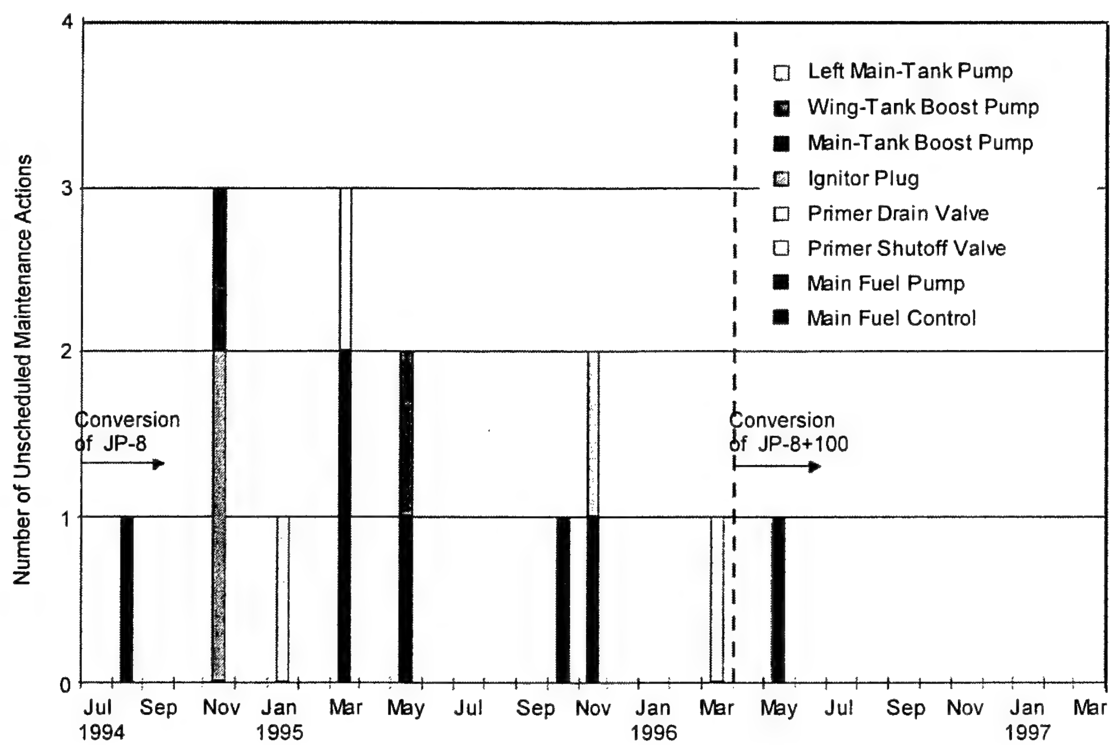


Figure 19 Historical Summary of Unscheduled Maintenance Actions on Tracked Items (Test and Control Aircraft)

The reduction in maintenance activity on tracked items cannot be attributed to a reduction in flying time since the monthly averages were about the same before and during the test period.

Figure **20** presents the related maintenance costs. The maintenance costs included both the cost of the item and associated labor requirements for replacing it. The fuel control is clearly the maintenance cost driver among the tracked items, as illustrated in Figure **21**.

Of the four fuel controls replaced prior to the test period, two were on test aircraft and two were on control aircraft. Thus, the reduction in the replacement rate of fuel controls cannot be attributed to the conversion to JP-8+100.

The other maintenance actions before the test period were simply one or two sporadic incidents each on a small number of items; these incidents presented no pattern and could not be attributed to the fuel.

Aborts

Detailed summaries of the causes for aborts for the test aircraft and the control aircraft respectively are presented in Tables 9 and 10. Figure 22 shows the abort history for the test and control aircraft before and during the test period. Figure 23 combines these data with the flight hours from Figure 18 to show the cumulative average flight hours per abort. During the pretest period on JP-8, the test aircraft had significantly more flight hours per abort than the control aircraft; however, this appears to have evened out just before the conversion of the test aircraft to JP-8+100. During the test period, the test aircraft had a slightly higher average of flight hours per abort than the control aircraft.

To draw conclusions about the impact of JP-8+100, one must look at the reasons for the aborts. The detailed reasons for the aborts listed in Tables 9 and 10 are tedious to sort through since most occurred only once or twice over the program period. To facilitate comparison, causes for aborts have been sorted into the following general categories:

- Aircraft electrical
- Aircraft mechanical/hydraulic
- Aircraft fuel system
- Engine electrical
- Engine mechanical/hydraulic
- Engine fuel system
- Computer system, sensors, and instrumentation
- Miscellaneous cockpit problems
- Auxiliary power unit (APU)
- Weapons systems
- Bird strikes

Figure 24 compares the totals of categories for *cause of abort* for the test aircraft before and after the conversion to JP-8+100; Figure 25 is a similar comparison for the control aircraft. It can be seen that the fuel systems are rarely the cause of aborts. Before the conversion, there were two fuel-system leaks on the test aircraft; after the conversion there were none. Conversely, for the control aircraft there were no fuel leaks prior to the test period and four during the test period.

Since these were all isolated incidents with no commonality, it seems safe to say that using JP-8+100 did not cause any operational problems, nor did it resolve any.

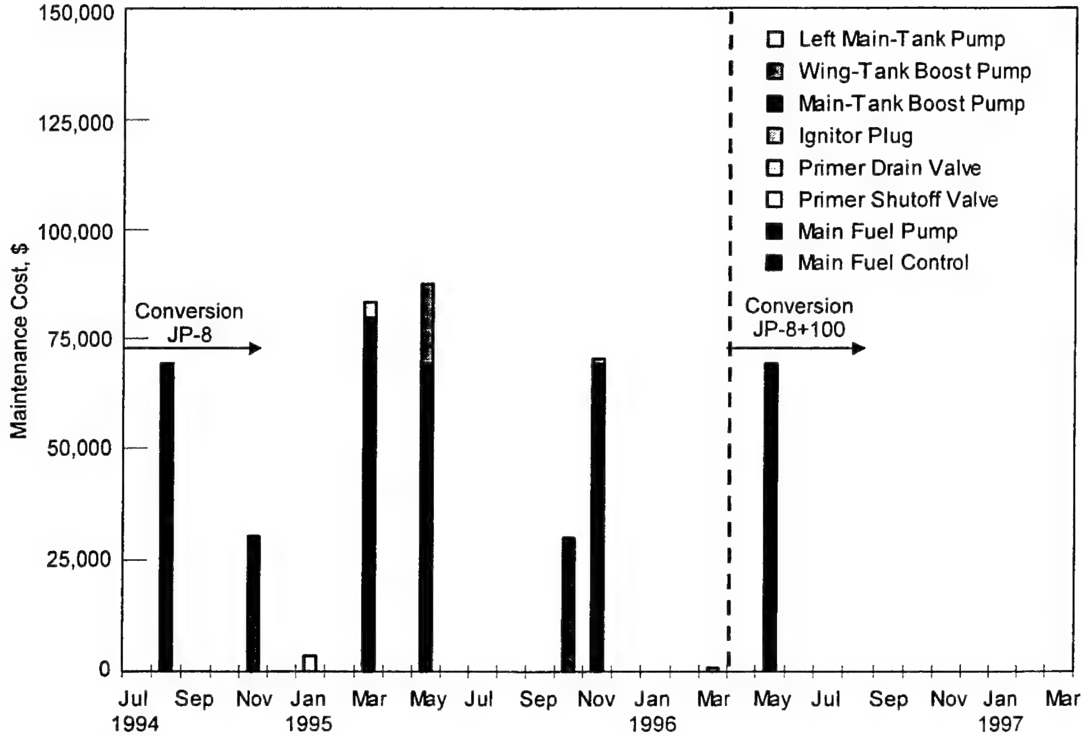


Figure 20 Historical Summary of Costs of Unscheduled Maintenance of Tracked Items (Test and Control Aircraft)

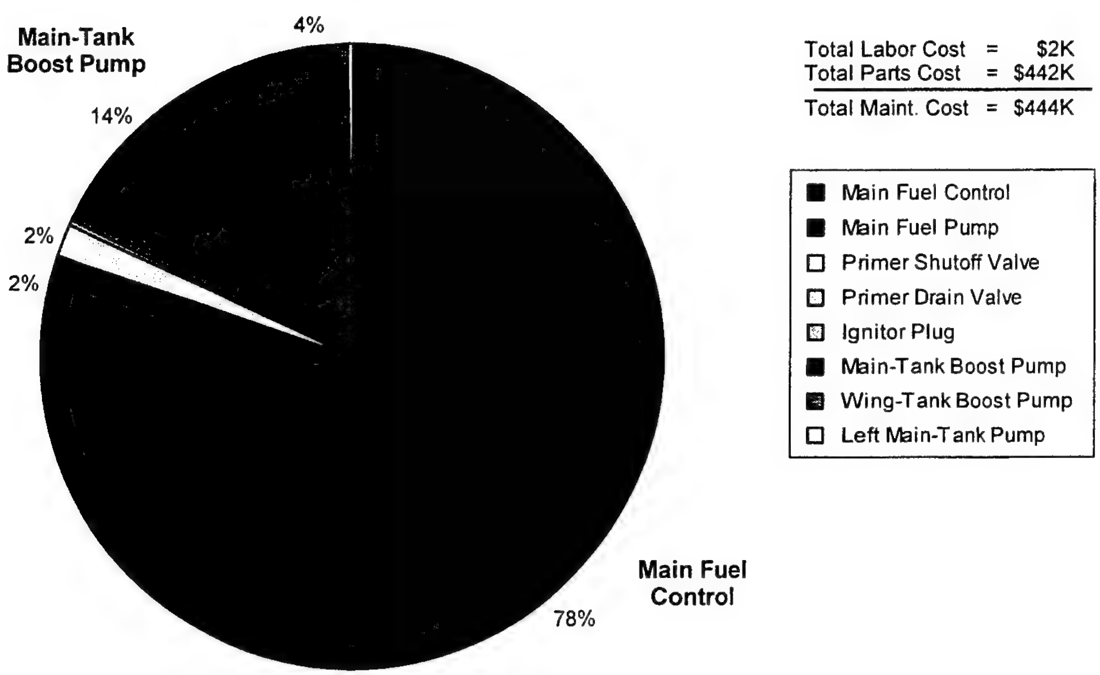


Figure 21 Cost Drivers for Unscheduled Maintenance on Tracked Items (Test and Control Aircraft)

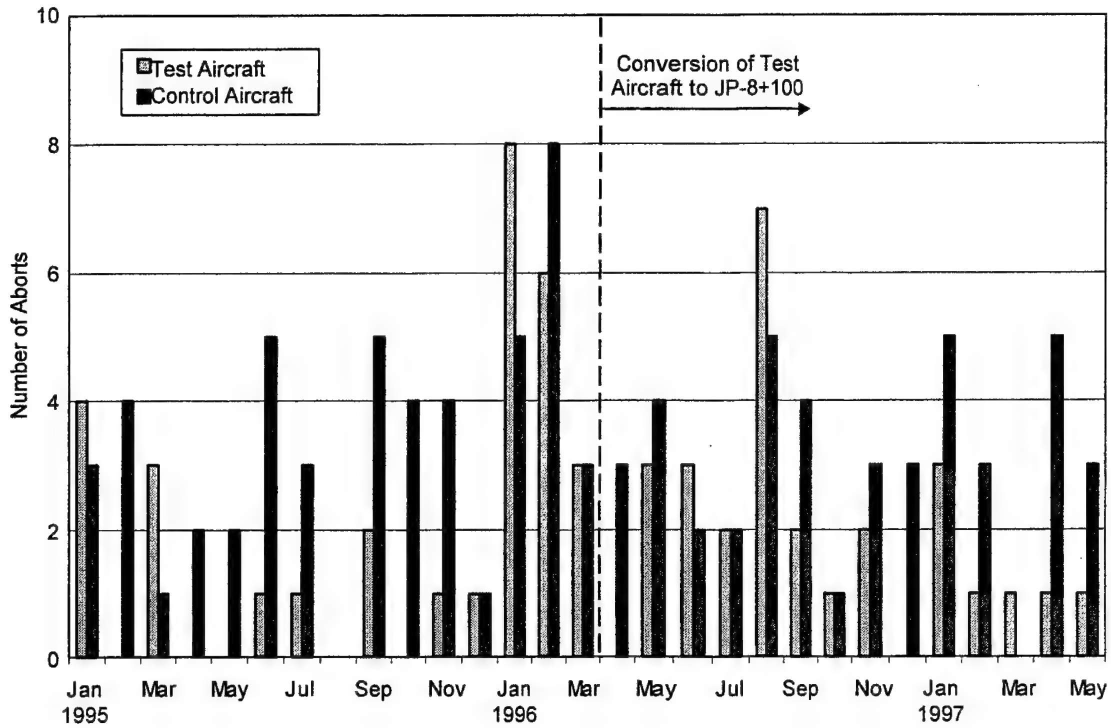


Figure 22 Summary of Monthly Aborts for Test and Control Aircraft

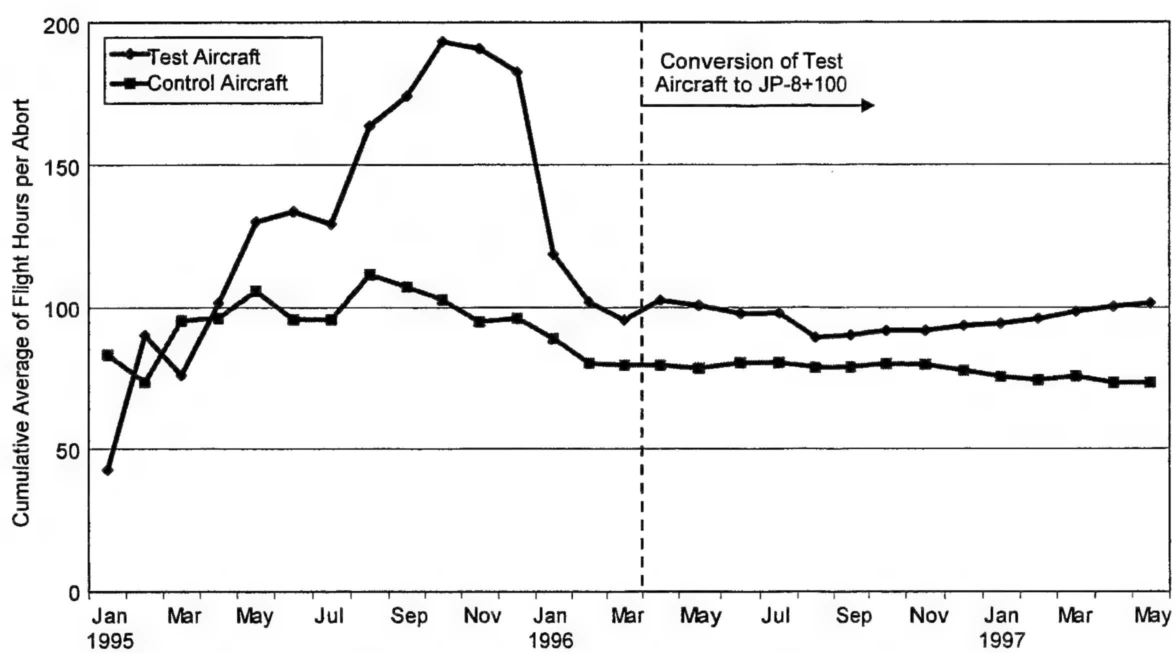


Figure 23 Comparison of Abort Rates for Test and Control Aircraft

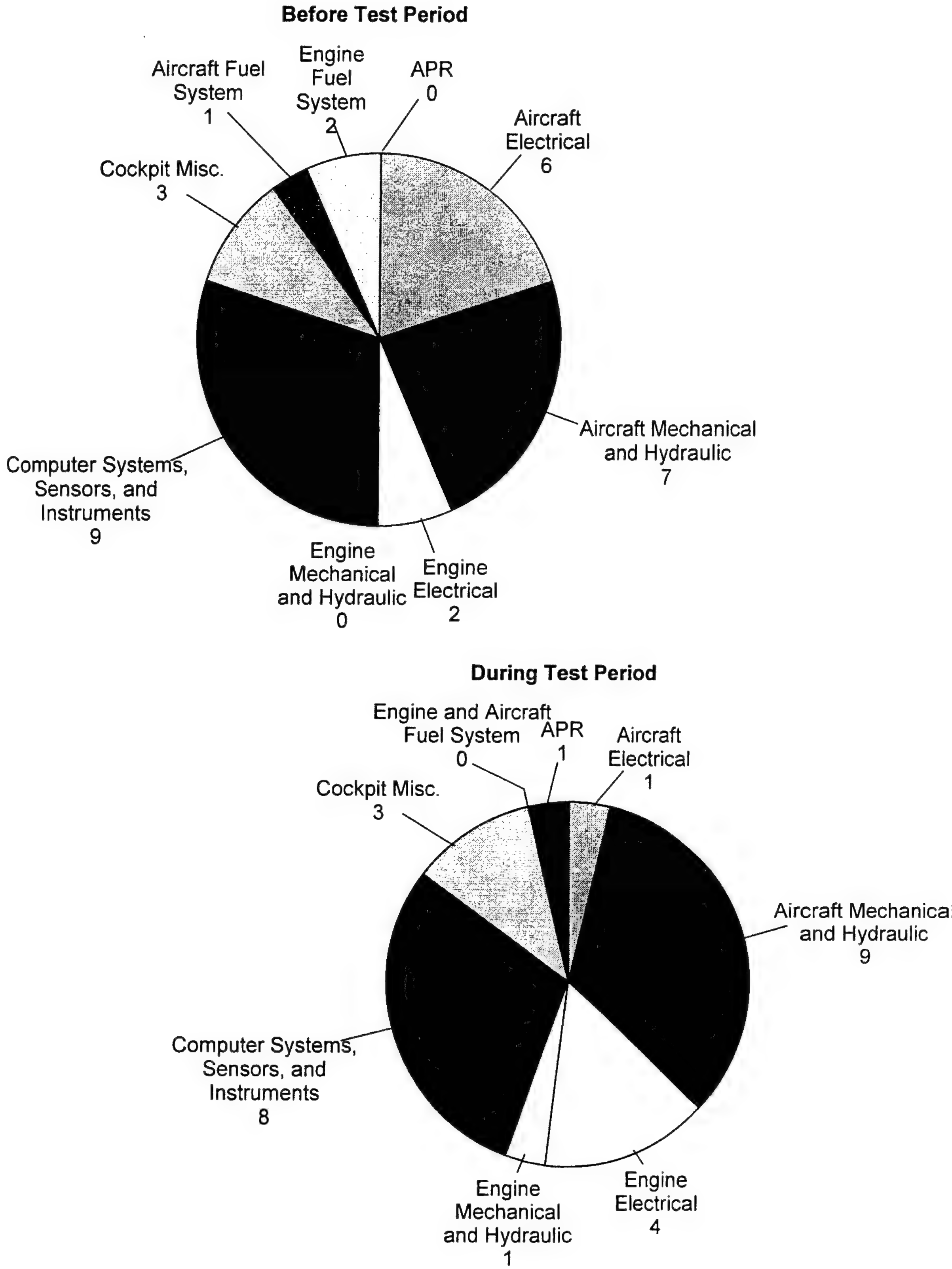


Figure 24 Summary of Causes for Aborts for Test Aircraft

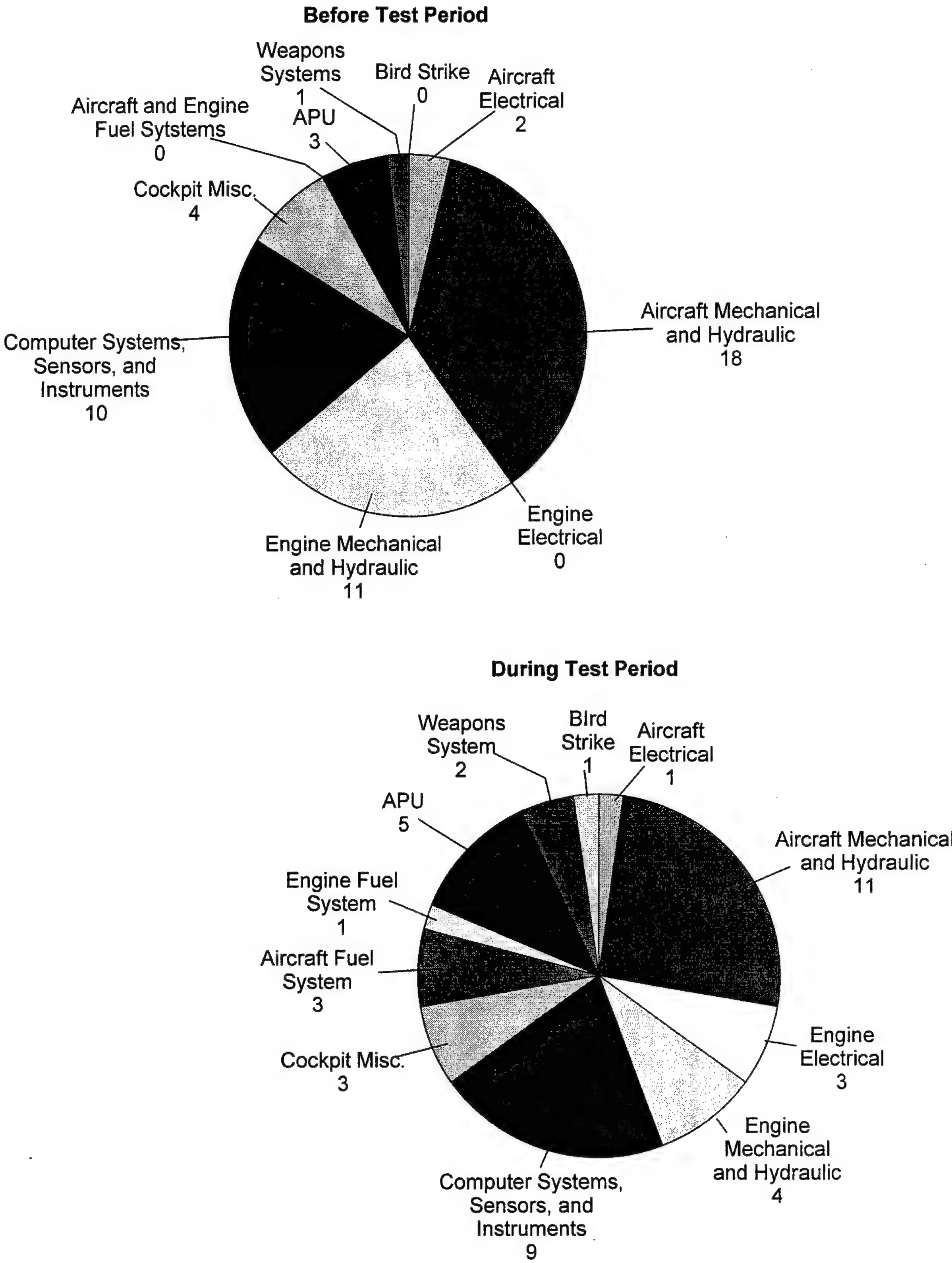


Figure 25 Summary of Causes for Aborts for Control Aircraft

Tear-Down Inspection

An SwRI staff member was able to participate in a scheduled tear-down inspection of test engine E205568. This engine had a total of 5577 hours since overhaul, the last 438 hours after the conversion to JP-8+100; maintenance personnel of the 104th FG estimated that probably about 25% of these hours were on JP-8 when refueled at other bases.

Visual inspections were made of the major components of interest:

- Fuel atomizers
- Turbine lades
- Combustor liner
- Guide vanes

Two other TF34 engines of comparable time, but on JP-8 only, had also been torn-down and were available for comparison. These engines had 4500 and 5547 hours since overhaul.

Fuel Atomizers and Swirl Cups - The exit cones of the fuel nozzles on the JP-8+100 test engine were very clean and shiny, but there were significant frangible carbon deposits that extended beyond the trailing edge on the swirl cups. The fuel-nozzle exit cones on the two JP-8 engines were also clean and shiny; likewise, the surfaces of the swirl cups were coated with frangible carbon deposits that appeared very similar to those on the test engine — including the extension beyond the trailing edge. It was concluded that the use of JP-8+100 did not reduce the deposits on the fuel atomizers but did not make the situation any worse either.

There were dark-brown, varnish-like deposits on the baffle around the swirl cups of the test engine, but again these appeared the same as on the JP-8 engines.

Combustion Chamber - The walls and dome of the combustor liner from the test engine were quite clean with just an occasional dusting of light carbon. There were no apparent differences from the two engines operated on JP-8.

High-Pressure Turbine and Guide Vanes - The blades of the high-pressure turbine were essentially the same for all three engines. There were some variations in color and damage to the leading edges, but the maintenance personnel said these differences were not unusual and were relatable to differences in turbine inlet temperatures as the engines age and suffer power degradation.

Low-Pressure Turbine Blades and Guide Vanes - The only major differences were found on the low-pressure turbine blades and guide vanes. On the JP-8+100 test engine, the first-stage LPT blades were magenta (bright reddish purple) on both the pressure side and the suction side. This coloring was heaviest on the leading edge of the outer 2/3 of the blade; there was very little coloring at the root. In the second, third, and fourth stage this gave way to a whitish coloring on the blades. In contrast, all of the LPT blades on the JP-8 engines were rust colored. Also, the blades were smooth to the touch on the JP-8+100 engine but very rough on the JP-8 engines.

At the entrance to the LPT, the third-stage guide vanes were magenta colored from the midsection out on the suction side and greenish white at the root; on the pressure side, the coloring was greenish white. In contrast, these guide vanes on the JP-8 engines were rust colored at the root and sooty black on the outer 2/3 of the length on both the suction and pressure sides. Samples were taken of the colored surface deposits from the JP-8+100 and JP-8 engines by wiping a soft paper towel over the surfaces. The wipings were analyzed at SwRI by x-ray fluorescence for the following elements:

- P, phosphorus
- Co, cobalt
- S, sulfur
- Ca, calcium
- Fe, iron

- Ni, nickel
- Zn, zinc
- Pb, lead
- Ba, barium
- Sn, strontium

(Note: several of these are irrelevant but were simply part of the standard analysis package.)

Figures **26** and **27** summarize the results of these analyses from the blade deposits as well as the paper towel itself. The only significant contribution from the paper towel was Ca; small quantities of S and P were also found. The major differences between the blade analyses are the increases in P and Co in deposits from the engine operated on JP-8+100. Concentrations of the other constituents were essentially the same.

The magenta coloring has been seen on other engines with high-temperature alloys containing cobalt; the cobalt combines with the phosphate in the +100 additive package to form the magenta-colored cobalt phosphate. A metallurgical investigation is not within the scope of this program but is being conducted by GEAE and the Air Force elsewhere.

Based on the visual inspection and setting aside any possible consequences of the magenta cobalt phosphate coating, it was concluded that after 400+ hours of operation on JP-8+100, there had been no detrimental effect on durability of the TF34 engine. On the +100 engine, there were no soot deposits on the turbine blades, but elsewhere deposits seemed about the same. It is not known by the why the LPT blades from the JP-8+100 engine had smoother surfaces than the LPT blades on the JP-8 engines.

3.5.1.3 Summary and Conclusions

JP-8+100 has been evaluated for potential effects on maintenance and reliability of TF34-GE-100 engines as used to power the A-10 aircraft. This was accomplished by first identifying critical components of the engine fuel system and hot section and then monitoring the unscheduled maintenance actions on these items for a period of 14 months at the 104^{th} Fighter Group. Eight of the seventeen aircraft assigned to the 104^{th} FG were converted to JP-8+100, while the other nine aircraft remained on JP-8. Maintenance and abort data for the eight test aircraft were compared with that of the nine control aircraft. Historical data for the 15 months prior to the test period were also collected for both sets of aircraft and used to evaluate the impact of JP-8+100 on the TF34 engine. The evaluation of the maintenance data included visits to the 104^{th} FG for discussions with the engine maintenance unit.

The only significant difference between the test engine and the two control engines were the appearance of the surfaces of the LPT blades and guide vanes. On the test engine, the blade surfaces were magenta on the first stage and transitioned through green to greenish-white on the fourth stage; in contrast, on the control engines both surfaces tended to be rust colored on all four stages.

Although there were differences in the abort rates and overall maintenance actions of tracked items before and during the test period, none could be attributed to JP-8+100. The prime example is the fuel control, which was the maintenance cost driver. In the 15 months prior to the test period, four fuel controls had been replaced; two of these were on test aircraft and two were on control aircraft. Thus, the reduction in replacement of fuel controls during the test period was common to both sets of aircraft and cannot be attributed to the fuel change.

No abort could be attributed to the fuel. It is therefore concluded that, for this 14-month demonstration test, JP-8+100 had no significant impact on maintenance costs of the TF34-GE-100 engines. There were no discernible benefits or detriments.

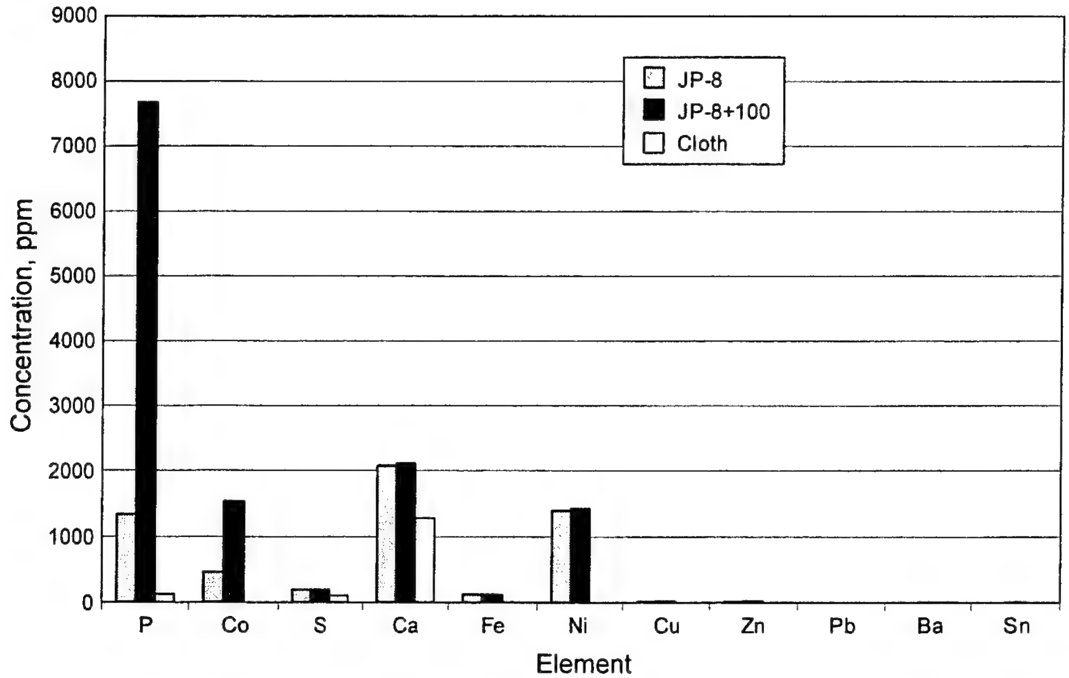


Figure 26 Elemental Analysis of Surface Coating From 1st Stage Turbine Blades of TF34 Engines Operated on JP-8 and JP-8+100

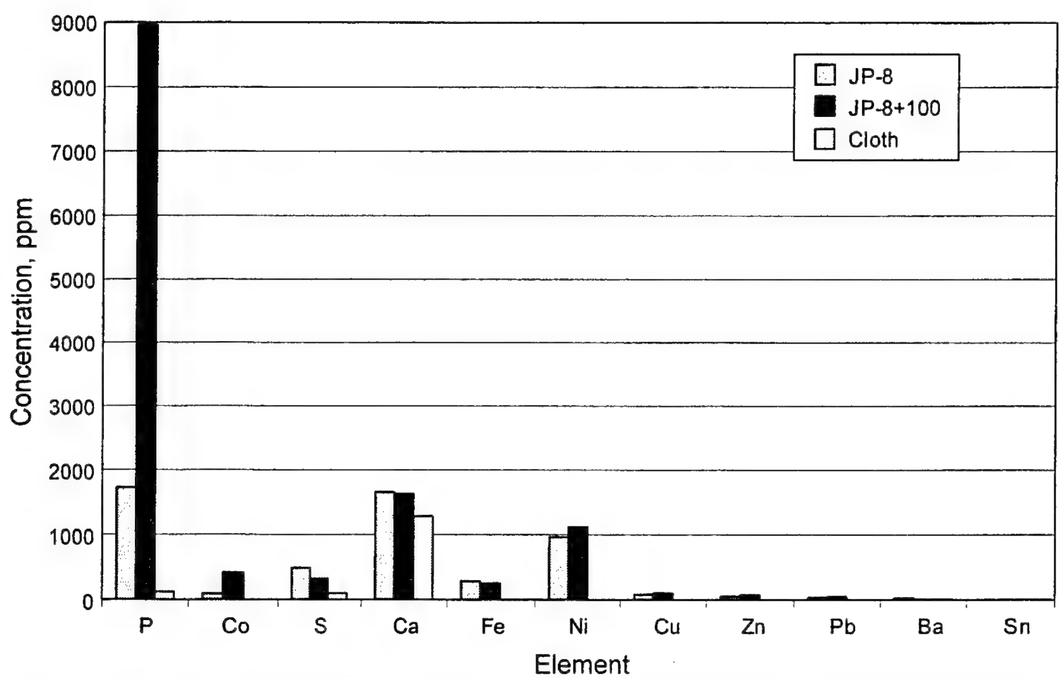


Figure 27 Elemental Analysis of Surface Coating From 4th Stage Turbine Blades of TF34 Engines Operated on JP-8 and JP-8+100

3.5.1.4 Recommendations

It appears that, on the TF34 engine, the only significant fuel deposits occur on the fuel-nozzle swirl cups. These deposits were not reduced with JP-8+100. It is recommended that a study be conducted on the mechanism of deposit formation on the fuel-wetted surface of swirl cups to determine (1) the role of fuel thermal stability on this problem area and (2) why the +100 concept is not effective. The results of such a study would lead to a laboratory test for screening the effectiveness of future thermal-stability additives, that is for JP-8+225, for reducing these deposits.

3.5.2 F110-GE-100

The purpose of this project was to determine the effect of using JP-8+100 fuel on the maintenance and operation of F110-GE-100 aircraft engines used on the F-16C/D aircraft. A field demonstration had been established by personnel from AFRL/PRSF at WPAFB with the 178th FW of the ANG at the Springfield Base in Ohio. The demonstration was conducted by converting all 18 aircraft assigned to the 178th FW to JP-8+100 for a period of 37 months; there were no control aircraft. After using JP-8+100 for 37 months, the unit was transferred to nearby Wright-Patterson AFB while maintenance was performed on the airfield at Springfield. At this time the 178th FW reverted to using JP-8. Before terminating the impact study, data were collected for another six months to determine if there was any immediate impact of the change back to JP-8 on maintenance and operations.

SwRI, under subcontract to GEAE, had the responsibility to collect and evaluate the maintenance data on the test aircraft; abort data were also collected to relate to operational problems and maintenance activity. The information was provided on a monthly basis to SwRI by maintenance and logistics personnel of the 178th FW. As part of the evaluation, visits were made to the engine maintenance unit of the 178th FW to review the results and verify the conclusions; these visits were made once a quarter and again at the end of the evaluation period.

This subsection reports the maintenance and abort data collected by SwRI and evaluation of the data.

3.5.2.1 Field Demonstration Program

A coordination meeting to initiate the field demonstration program was held at the 178th FG of the Ohio ANG at Springfield-Beckly Municipal Airport on July 19, 1996. Attending the meeting were representatives from the Command Group, the Engine Maintenance Section, and the Engine Management Section of the 178th FG; the Propulsion Directorate at Wright-Patterson AFB (WPAFB); GEAE, and SwRI. It was decided that all 18 aircraft of the 178th FG would participate in the demonstration and fly on JP-8+100; there would be no control aircraft flying on JP-8. The impact of JP-8+100 would be evaluated by comparing maintenance and abort data during the program with historical data taken when the 178th FG was flying on JP-8.

Engine/Aircraft Description

The test aircraft used for the demonstration were F-16C/D *Falcons* each powered by a single F110-GE-100 turbofan with afterburner. There were 33 engines involved in the program. If an engine were brought in for extensive maintenance or shipped to depot for overhaul, the engine would be replaced in the airframe by another engine that then became a part of the program. Table 11 lists the serial numbers of the engines that participated in the test program, the tail number of the aircraft into which they were initially installed, the date the engine entered the demonstration program, and the total number of operating hours on JP-8+100. The sum total of Group operating hours is 8740.6.

Data Collection

The JP-8+100 evaluation period was 37 months, from the beginning of September 1996 through the end of September 1999. A historical evaluation was made by collecting data on unscheduled maintenance for the selected engine items for the 23-month period that the 178th FG flew on JP-8 prior to the +100 evaluation period. Historical data on causes for flight aborts were only available for the eight months prior to the test period.

The maintenance evaluation was conducted on the airframe, engine fuel systems, and hot-section components considered likely to be affected by the fuel change; these components were selected by GEAE. A copy of the Technical Order for the F-110 aircraft was obtained, and copies of the WUC's were provided to GEAE to identify fuel and hot-section components to be tracked on the test aircraft during the demonstration program. Table 12

identifies the components selected by GEAE for tracking and the WUC's. It should be noted that replacements of fuel nozzles are not tracked in the databases and thus do not appear in this study as there was no way to track them.

Only those components replaced during unscheduled maintenance actions were considered for analysis. The data on unscheduled maintenance actions were gathered from the CEMS and provided to SwRI by the 178th Engine Management Branch (LSF-LGL).

Maintenance costs were determined on the basis of the cost of the component and the standard labor requirement and rates for that action as of 1996-7. Costs of the items and labor rates were obtained from the 178th FG Budget Analysis Branch (LSF-LGLX). For the analysis, the replacement costs of the items were kept constant over the period of the investigation so that the results would not be skewed by inflation. These costs are summarized in Table 13.

Data on the number of aborts and their causes were obtained from the 178th FG Data Analysis Branch (LSF-LGLP).

Table 11 Identification of Test Engines and Aircraft

Engine Serial Number	Aircraft Tail Number	Date Entered Program	Months on JP-8+100	Total Operating Hours on JP-8+100	Total Hours on Engine
E9191	A0268	Sept 1996	27	141.2	2010.4
E9250	A0222	Sept 1996	16	43.1	2220.0
E9289	A0315	Sept 1996	14	352.9	2177.1
E9395	-	Apr 1997	13	246.5	2139.4
E9498	A0047	Nov 1996	24	381.1	2435.0
E9502	A0327	Oct 1996	7	158.9	1664.2
E9512	A0243	Oct 1996	16	344.5	2722.8
E9574	-	Apr 1997	16	387.7	1930.6
E9613	-	Sept 1997	16	306.4	1967.4
E9620	A0382	Sept 1996	30	393.7	2850.5
E9673	A0342	Oct 1996	24	393.4	2159.8
E9689	A0350	Sept 1996	14	405.1	2170.3
E9699	A0245	Sept 1996	29	459.0	2410.9
E9734	A0271	Oct 1996	26	392.1	2004.7
E9819	A0283	Sept 1996	21	262.3	1811.1
E9856	A0364	Sept 1996	28	428.6	1797.1
E9955	A0302	Sept 1996	16	292.1	1793.6
E5126	A0276	Sept 1996	15	362.3	1508.5
E5208	A0217	Sept 1996	18	491.8	1912.5
E5234	A0372	Sept 1996	31	409.5	1706.7
E5264	A0262	Sept 1996	25	298.3	1540.6
E9307	-	June 1997	10	190.2	2010.2
E9111	-	Sept 1997	18	486.1	2198.2
E9607	-	July 1998	11	172.0	2085.7
E9151	-	Sept 1998	9	124.0	2262.4
E9916	-	Nov 1998	2	15.1	15.1
E9450	-	Jan 1999	9	160.8	2152.9
E9507	-	Jan 1999	5	51.2	2897.5
E9562	-	Feb 1999	8	164.9	2025.3
E9579	-	Dec 1998	4	41.1	2382.2
E5235	-	Dec 1998	10	116.3	1570.3
E5274	-	Feb 1999	6	136.3	515.6
E9961		Feb 1999	8	132.1	1907.7

Table 12 Component Work Unit Codes Tracked at the 178th FG

WCU	Component	WCU	Component
27CJG	Combustion Chamber Assembly	27EAO	Augmentor Assembly
27CJT	HPT Shroud Assembly	27ECO	Exhaust Nozzle Assembly
27CJM	HPT Nozzle Assembly	27GDC	Augmentor Fuel Pump
27CLG	HPT Rotor Assembly	27GAL	Main Engine Control
27DCO	LPT1 Nozzle Assembly	27GAH	Main Engine Fuel Pump
27DAO	LPT Rotor Assembly	27GAA	Engine Fuel Boost Pump
27DAB	Stage 1 Blade Assembly	27GPL	Augmentor Fuel Temp Control
27DAK	Stage 2 Blade Assembly	27GDH	Augmentor Fuel Control
27DDO	LPT2 Nozzle Assembly	27GAU	Fuel/Oil Cooler
27DEO	Turbine Frame Assembly		

Table 13 Summary of Parts and Labor Costs

Engine operating time (EOT) was also obtained from LSF-LGLPA. Engine hours were adjusted when test aircraft were deployed from their home base to locations where JP-8+100 was not available and they flew on JP-8. The JP-8 hours were not counted.

3.5.2.2 Data Evaluation

Three sets of data are presented and discussed: (1) engine/airframe hours, (2) unscheduled maintenance actions on tracked items, and (3) aborts. In each case, three time periods will be used to discuss the data and draw conclusions concerning the effect of JP-8+100 on maintenance and operations of F110 engines:

1. A period of time before the demonstration program when the aircraft of the 178th FG were operating on JP-8. For the abort data, this was a 20-month period from January 1995 through August 1996; for the maintenance data, this was an 8-month period from January 1996 through August 1996.

2. The 37-month demonstration program from September 1996 through September 1999.

3. The 6-month period immediately following the demonstration program when the 178th FG returned to operating on JP-8.

Engine Operating Time

Detailed data for operating hours of the engines are provided in Tables 14 through 25. Figure 28 presents historical data of total flight hours per month on JP-8+100 for the three periods of the evaluation. The three colored bars superimposed on the history graphs show average flight hours during each of the three periods. The important thing

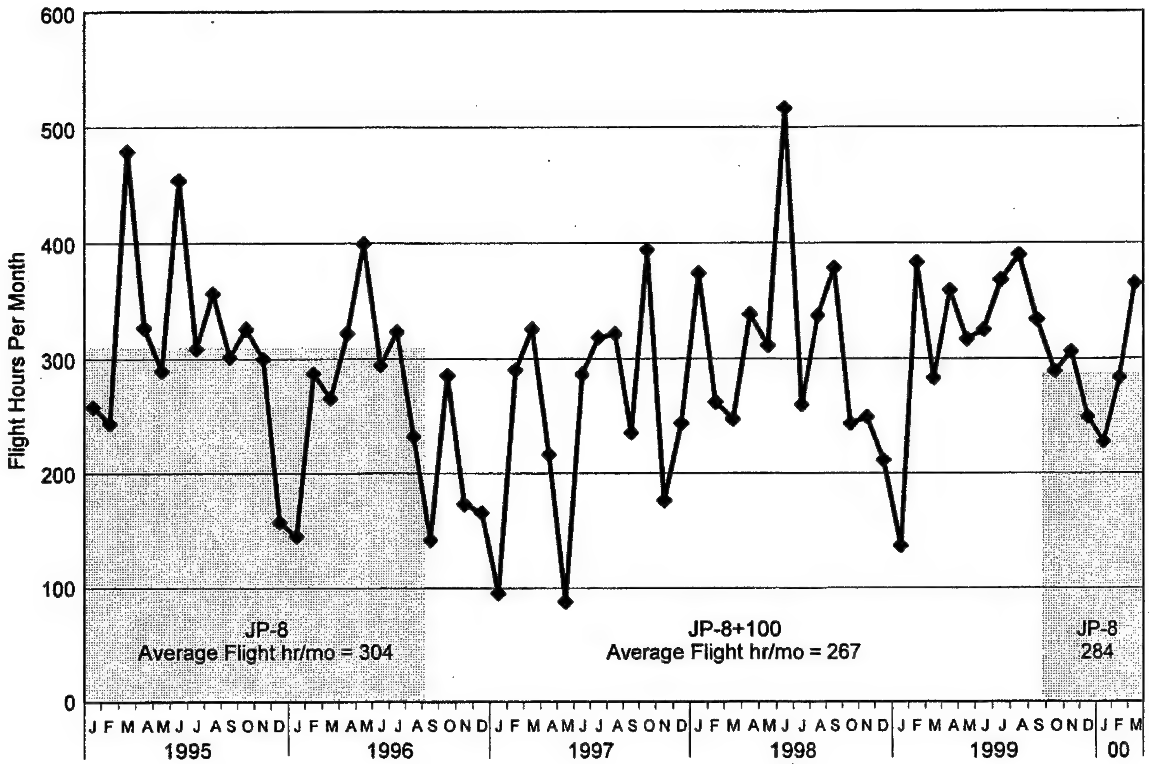


Figure 28 Summary of Monthly Flight Hours

to note is that the test aircraft averaged about the same number of flight hours per month in each of the three periods; thus, changes in maintenance requirements or abort numbers are not due to significant changes in the flight hours per month.

Table 14 **Monthly Flight Hours Before Test Period**
Data not available for specific engines.

Month		Total Engine Hours
1994	October	N/A
	November	291.7
	December	305.8
1995	January	228.4
	February	243.7
	March	479.1
	April	327
	May	289.4
	June	454.2
	July	308.5
	August	356.1
	September	301.6
	October	325.9
	November	300.1
	December	157.1
1996	January	144.9
	February	287.5
	March	265.9
	April	322.1
	May	399.3
	June	294.3
	July	323.0
	August	187.7

Table 15. **Summary of Flight Hours Using JP-8 After Returning to JP-8 Following Test Period**
Data not available for specific engines.

Month		Total Engine Hours
1999	October	289.3
	November	305.9
	December	249.8
2000	January	227.7
	February	283.7
	March	264.9

Table 16 Monthly Flight Hours <u>During</u> the Test Period

Engine Serial No.	1996				1997											
	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
9191	7.2	26.2	16.7	17.2	13.2	25.7	31.8	17.0			37.5	30.6	29.0	18.5	0	0
9250	7.9	27.8	7.4													
9289	15.1	30.0	10.3	shop	shop						32	29.5	19.5	35.4	0	32.9
9395									5.8	50.3	34.5	11.8		11.7	shop	shop
9498			8.0	4.1	6.3	14.9	28.5	21.5	6.0		1.4	12.6	18.1	14.4	6.4	12.3
9502		29.6	14.9	9.4	25.0	10.1	42.9	27.0								
9512		19.5	2.2	0	16.1	20.7	36.8	25.1	10.8	33.7	2.5	8.2		shop	0	shop
9574								13.5	5.3		64.7	28.3	32.1	36.1	5.2	shop
9613													16.1	33.1	0	0
9620	4.0	12.0	17.6	21.0	0	6.8	27.8	30.8	8.0	19.1	14.7	13.1	8.7	10.4	20.4	0
9673		29.1	18.1	4.5	24.7	18.0					6.1	17.3	28.3	11.3	shop	8.6
9689	21.7	21.9	23.6	6.2	10.1									shop	shop	shop
9699	41.1	6.0	0	0.5	shop		10.0	15.3	4.0	43.0	9.7	21.5	16.9	25.5	4.2	21.5
9734		12.9	10.5	20.8	0	29.6	36.3	23.2	15.3					0	0	0
9819	8.6	32.9	2.0	22.2	0	20.5					18.0	46.1		21.0	19.7	30.8
9856	3.8	10.6	3.3	24.0	0	40.7	26.7	24.7	13.8	37.7				36.2	23.0	32.8
9955	1.0	20.7	3.8	19.4	0	24.0	43.4	15.3	1.1	38.8	28.3	33.8	7.8	39.0	1.2	5.7
5126	9.7	0	0.9	5.5	0	24.2						22.1	18.7	8.9	9.9	16.7
5208	8.2	0	9.0	shop	shop						12.7	9.2	3.8	19.4	20.6	22.8
5234	10.5	16.9	11.2	shop	shop	40.0	41.6	3.1	8.1	26.4	21.5	11.2	15.5	12.5	29.5	12.5
5264	2.7	12.5	13.4	10.8	0	15.2			9.6		0.7	16.8		0	0	9.6
9307										37.4	20.5	9.5	20.0	29.8	20.0	19.0
9111													1.1	30.7	16.0	19.0

Table 16. Monthly Flight Hours <u>During</u> the Test Period (Concluded)

Engine Serial No.	1998												1999								
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
9191	0	0	13.0	19.3	10.2	shop	26.3	29.7	10.7	shop	shop	6.3	3.0	4.2	12.4	38.9	12.9	shop	9.7	56.8	8.7
9520																					
9289	3.7	1.0	7.1	shop	22.0	13.6	0.8	40.1	34.2	11.8	6.1	shop	1.5	shop	shop	shop	shop	shop	0	0	
9395	0	34.2	12.6	20.2	30.8	2.4	13.3	14.0	4.9												
9498	4.7	17.6	8.6	22.2	31.1	10.4	8.4	18.8	22.5	40.5	9.6	01.2	1.1	30.8							
9502																					
9512	0	26.9	14.8	13.8	shop	shop	shop	shop	shop	shop	shop	shop	shop	shop	1.1	30.4	11.3	20.9	12.4	70.4	17.6
9574	28.8	5.5	25.5	16.3	13.2	13.2	13.2	13.2	0	12.3	0	5.2	5.9	shop	shop	9.9	34.0	0	17.0	0	shop
9613	0	0	0	0	10.1	21.4	12.6	15.7	42.2	24.1	9.8	5.2	0	11.1	11.1	13.2	8.0	13.0	24.0	36.6	14.8
9620	0.9	16.4	12.8	12.6	18.5	0	6.2	30.3	45.0	29.1	2.5	8.0									
9673	0	24.5	31.2	8.5	0	0	0	0	0	30.3	5.0	5.0	0	0	15.2	11.1	20.5	29.6	13.4	63.1	15.1
9689	shop	shop	shop	17.3	19.4	2.4	28.2	26.0	35.4	4.9	12.0	3.7	4.9	37.5	30.0	26.9	17.8	0.7	15.6	33.9	5.9
9699	21.5	shop	shop	shop	11.1	8.9	19.1	4.4	17.9	28.1	3.4	19.1	2.9	0	13.1	28.7	28.6	12.1	26.9	30.8	0
9734	0	0	10.4	23.0	8.3	6.5	2.9	20.1	29.1	46.8	9.2	14.4	7.1	16.7	6.0	17.0	0	0.9	3.7	46.6	0.7
9819	21.2	11.9	3.3	shop	shop	shop	shop	shop	shop	shop	shop	shop	shop	shop	shop	shop	shop	shop	shop	shop	shop
9856	6.7	25.4	18.8	14.7	25.3	7.2	34.0	5.3	shop												
9955	8.8	shop																			
5126	0	0	4.8	22.8	20.6	0.9	shop	shop	shop	24.6	13.8	31.9	5.9	33.8	18.5	10.6	18.6	5.0	10.7	23.2	0
5208	4.3	13.1	7.9	18.6	38.6	0	25.3	26.4	27.7	20.2	7.9	16.5	7.6	34.9	23.1	0	17.2	20.2	33.9	43.6	13.9
5234	3.4	17.8	38.1	28.9	23.8	shop	15.5	0.3	17.1												
5264	2.8	28.3	16.9	21.8	30.0	6.1	7.1	0	19.6	0	0	0	3.5	35.7	22.7	1.7	shop	shop	shop	0	3.6
9307	12.1	0	6.6	15.3																	
9111	2.3	shop	15.5	25.8	26.2	7.8	32.0	28.7	30.0	16.3	9.6	28.5	2.3	20.0	11.5	shop	11.0	9.6	8.4	70.6	14.0
9607						0	5.9	15.2	21.6	29	1.6	17.5	9.8	22.0	14.9	32.1	2.4	shop	shop	shop	0
9151									15.6	2.4	1.5	7.9	0	24.8	13.2	7.0	20.3	33.3			
9916										0	6.6	8.5	shop	shop	shop	shop					
9450												0	1.4	25.9	23.1	25.7	9.6	22.9	25.3	46.2	6.4
9507												0	1.8	0	0	0	0	0.9	22.7	58.9	7.8
9562												shop	0	22.9	34.0	30.9	23.4	5.6	15.7	72.4	6.6
9579												9.8	0	9.0	22.3						
5235												1.4	0	3.8	17.0	13.0	29.3	13.0	29.7	15.4	0
5274													0	39.8	22.1	0	27.3	0	26.1		
9961															20.6	30.5	21.9	30.5	1.8	23.1	15.6

Table 17 **Summary of Unscheduled Maintenance Actions on Tracked Items Prior to JP-8+100 Test Period**

Unscheduled Maintenance Item	1994			1995												1996							
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
Main Engine Control	1					1								1			4	1			1		
Main Fuel Pump		1					1						1				1						
Augmentor Fuel Pump									1					1	1		1	2					1
Augmentor Fuel Control			1		1			1									1						
AFT Control		1			1				1				1				1	3					
Combustor Chamber Assembly		1						2	1	3		1					1				1		
HPT Shroud Assembly							1			1						1	1				2		
HPT Nozzle Assembly						1				1							1				1		
LPT1 Nozzle Assembly					1	2			1					1		2	1				1		
LPT2 Nozzle Assembly																							
LPT Rotor Assembly										1													
Turbine Frame Assembly	1		1	2	1	2	1			1		1					1			1	1		
Augmentor Assembly													1								1	1	
Augmentor Exhaust Nozzle																							
Fuel/Oil Cooler																							

Table 18 **Summary of Unscheduled Maintenance Actions on Tracked Items During JP-8+100 Test Period**

Unscheduled Maintenance Item	1996				1997												1998												1999								
	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Main Engine Control						1				1							1										1										1
Main Fuel Pump																		1	1																1	1	
Augmentor Fuel Pump						1	1															2					1							1		1	
Augm'tor Fuel Control		1											1									1										1					
AFT Control	1										1						1		1	1	2				1	1			1			1					1
Comb. Chmbr Assy		1	1								1											1		1													
HPT Shroud Assy		1	1	1																									1								
HPT Nozzle Assy				1													1						1					1	1								
LPT1 Nozzle Assy					1																								1				1				
LPT2 Nozzle Assy																													1								
LPT Rotor Assy						1													1																		
Turbine Frame Assy		1	1																														2				
Augmentor Assy	1	1		1	1	1																			1												2
Augm'tor Exh Nozzle				1																																	
Fuel/Oil Cooler				1																																	

Table 19 **Summary of Unscheduled Maintenance Actions on Tracked Items After Returning to JP-8 Following Test Period**

Unscheduled Maintenance Item	1999			2000		
	O	N	D	J	F	M
Main Engine Control						
Main Fuel Pump	1					
Augmentor Fuel Pump		1		1		
Augmentor Fuel Control						
AFT Control			1	1		
Comb. Chmbr Assy						
HPT Shroud Assy						
HPT Nozzle Assy				1		
LPT1 Nozzle Assy						
LPT2 Nozzle Assy						
LPT Rotor Assy						
Turbine Frame Assy	1					
Augmentor Assy						
Augmentor Exh Nozzle						
Fuel/Oil Cooler						

Table 20 Summary of Reasons for Unscheduled Maintenance Actions on Tracked Items

WCU = Work Unit Code, defines the item; HMC = How Malfunction Code, describes the problem.

WUC	Component Nomenclature	HMC	Reason for Replacement	Date	Fuel
27GAL	Main Engine Control	198	Contaminated Fuel	28-Oct-94	JP-8
		223	Control System Component Malfunction	24-Mar-95	
		537	Low Power or Thrust	27-Nov-95	
		223	Control System Component Malfunction	1-Feb-96	
		197	Fuel Leakage	4-Feb-96	
		223	Control System Component Malfunction	8-Feb-96	
		223	Control System Component Malfunction	8-Feb-96	
		561	Unable to Adjust to Limits	5-Mar-96	
		223	Control System Component Malfunction	21-Jun-96	
		231	Augmentor Blowout	6-Feb-97	JP-8+100
		223	Control System Component Malfunction	5-Jun-97	
		223	Control System Component Malfunction	28-Jan-98	
		223	Control System Component Malfunction	6-Nov-98	
		381	Leaking Internal or External	16-Sep-99	
27GAH	Main Fuel Pump	197	Fuel Leakage	10-Nov-94	JP-8
		223	Control System Component Malfunction	23-Apr-95	
		197	Fuel Leakage	24-Oct-95	
		223	Control System Component Malfunction	1-Feb-96	
		197	Fuel Leakage	12-Feb-98	JP-8+100
		197	Fuel Leakage	31-Mar-98	
		381	Leaking Internal or External	21-Jul-99	
		197	Fuel Leakage	18-Aug-99	
		381	Leaking Internal or External	20-Oct-99	JP-8

Table 20. Summary of Reasons for Unscheduled Maintenance Actions on Tracked Items (Continued)

WUC	Component Nomenclature	HMC	Reason for Replacement	Date	Fuel
27GDC	Augmentor Fuel Pump	223	Control System Component Malfunction	7-Jun-95	JP-8
		197	Fuel Leakage	13-Nov-95	
		197	Fuel Leakage	13-Dec-95	
		197	Fuel Leakage	5-Feb-96	
		197	Fuel Leakage	5-Mar-96	
		193	Excessive Stalls	5-Mar-96	
		197	Fuel Leakage	4-Aug-96	
		231	Augmentor Blowout	17-Jan-97	JP-8+100
		197	Fuel Leakage	5-Feb-97	
		223	Control System Component Malfunction	19-Jun-98	
		223	Control System Component Malfunction	19-Jun-98	
		197	Fuel Leakage	24-Nov-98	
		197	Fuel Leakage	16-Jun-99	
		197	Fuel Leakage	2-Sep-99	
		197	Fuel Leakage	23-Nov-99	JP-8
		197	Fuel Leakage	14-Jan-00	
27GDH	Augmentor Fuel Control	197	Fuel Leakage	19-Dec-94	JP-8
		177	High or Low Fuel Consumption	28-Feb-95	
		223	Control System Component Malfunction	2-May-95	
		223	Control System Component Malfunction	5-Feb-96	
		231	Augmentor Blowout	9-Oct-96	JP-8+100
		197	Fuel Leakage	17-Sep-97	
		223	Control System Component Malfunction	26-Sep-97	
		197	Fuel Leakage	29-Jun-98	
		197	Fuel Leakage	21-Apr-99	

Table 20. Summary of Reasons for Unscheduled Maintenance Actions on Tracked Items (Continued)

WUC	Component Nomenclature	HMC	Reason for Replacement	Date	Fuel
27GPL	Afterburner Fuel Temp Control	561	Unable to Adjust to Limits	18-Nov-94	JP-8
		223	Control System Component Malfunction	1-Feb-95	
		223	Control System Component Malfunction	10-Jun-95	
		223	Control System Component Malfunction	2-Oct-95	
		223	Control System Component Malfunction	1-Feb-96	
		223	Control System Component Malfunction	5-Mar-96	
		561	Unable to Adjust to Limits	5-Mar-96	
		223	Control System Component Malfunction	5-Mar-96	
		223	Control System Component Malfunction	10-Sep-96	JP-8+100
		223	Control System Component Malfunction	17-Jul-97	
		223	Control System Component Malfunction	14-Jan-98	
		223	Control System Component Malfunction	12-Mar-98	
		223	Control System Component Malfunction	2-Apr-98	
		223	Control System Component Malfunction	29-May-98	
		223	Control System Component Malfunction	30-May-98	
		242	Failed to Operate - Specific Reasons Unknown	19-Sep-98	
		242	Failed to Operate - Specific Reasons Unknown	15-Oct-98	
		223	Control System Component Malfunction	15-Jan-99	
		223	Control System Component Malfunction	30-Apr-99	
		223	Control System Component Malfunction	8-Sep-99	
		223	Control System Component Malfunction	22-Dec-99	JP-8
		315	Surges and Fluctuates	10-Jan-00	

Table 20. Summary of Reasons for Unscheduled Maintenance Actions on Tracked Items (Continued)

WUC	Component Nomenclature	HMC	Reason for Replacement	Date	Fuel
27CJG	Combustion Chamber Assy	188	Borescope Indicates Comb Section Deterioration	2-Nov-94	JP-8
		146	Combustion Damage	2-May-95	
		188	Borescope Indicates Comb Section Deterioration	30-May-95	
		188	Borescope Indicates Comb Section Deterioration	9-Jun-95	
		188	Borescope Indicates Comb Section Deterioration	16-Jul-95	
		183	Performance Indicates Comb Section Deterioration	20-Jul-95	
		188	Borescope Indicates Comb Section Deterioration	31-Jul-95	
		145	Cracked Diffuser Cases	27-Sep-95	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	21-Feb-96	
		147	Combustion Case Burn or Hot Spot	18-Jun-96	
		146	Combustion Damage	8-Oct-96	JP-8+100
		146	Combustion Damage	6-Nov-96	
		146	Combustion Damage	30-Jul-97	
		147	Combustion Case Burn or Hot Spot	18-Jun-98	
		146	Combustion Damage	11-Aug-98	
27CJT	HPT Shroud Assy	188	Borescope Indicates Combustion Section Deterioration	17-Apr-95	JP-8
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	6-Jul-95	
		189	Borescope Indicates Turbine Section Deterioration	23-Jan-96	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	21-Feb-96	
		189	Borescope Indicates Turbine Section Deterioration	31-Jul-96	
		146	Combustion Damage	31-Jul-96	
		189	Borescope Indicates Turbine Section Deterioration	8-Oct-96	JP-8+100
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	21-Nov-96	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	15-Dec-96	
		146	Combustion Damage	22-Jan-97	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	15-Jan-99	

Table 20. Summary of Reasons for Unscheduled Maintenance Actions on Tracked Items (Continued)

WUC	Component Nomenclature	HMC	Reason for Replacement	Date	Fuel
27CJM	HPT Nozzle Assy	153	Turbine Damage Due to Material Failure	24-Mar-95	JP-8
		189	Borescope Indicates Turbine Sec Deterioration	31-Jul-95	
		189	Borescope Indicates Turbine Sect Deterioration	21-Feb-96	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	31-Jul-96	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	17-Dec-96	
		146	Combustion Damage	10-Jan-98	JP-8+100
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	4-Jun-98	
		190	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	17-Dec-98	
		189	Borescope Indicates Turbine Section Deterioration	19-Jan-99	
		190	Cracked	4-Jan-00	JP-8
27DC0	LPT1 Nozzle Assy	152	Turbine Nozzle Failure	14-Feb-95	JP-8
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	8-Mar-95	
		152	Turbine Nozzle Failure	29-Mar-95	
		189	Borescope Indicates Turbine Section Deterioration	12-Jun-95	
		152	Turbine Nozzle Failure	15-Nov-95	
		458	Out of Balance	19-Jan-96	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	19-Jan-96	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	29-Feb-96	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	6-Jun-96	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	22-Jan-97	JP-8+100
		152	Turbine Nozzle Failure	19-Jan-99	
		190	Cracked	18-May-99	
	LPT2 Nozzle Assy	152	Turbine Nozzle Failure	17-Jan-99	JP-8+100
27DA0	LPT Rotor Assy	223	Control System Component Malfunction	9-Jul-95	JP-8
		690	Excessive Vibration or Rough Operation	22-Feb-97	
		425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	24-Mar-98	JP-8+100

Table 20. Summary of Reasons for Unscheduled Maintenance Actions on Tracked Items (Continued)

WUC	Component Nomenclature	HMC	Reason for Replacement	Date	Fuel
27DE0	Turbine Frame Assy	189	Borescope Indicates Turbine Section Deterioration	11-Oct-94	JP-8
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	22-Dec-94	
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	25-Jan-95	
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	30-Jan-95	
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	14-Feb-95	
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	7-Mar-95	
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	8-Mar-95	
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	4-Apr-95	
		153	Turbine Damage Due to Material Failure	1-Jul-95	
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	11-Sep-95	
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	27-Feb-96	
		195	Exceeding Quality Check Temperature Limit	31-May-96	
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	5-Jun-96	
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	9-Oct-96	JP-8+100
		148	Damaged, Cracked Turbine Frame Case (Burned Through)	14-Nov-96	
		191	High EGT	3-May-99	
		190	Cracked	19-May-99	
		190	Cracked	21-Oct-99	JP-8

Table 20. Summary of Reasons for Unscheduled Maintenance Actions on Tracked Items (Concluded)

WUC	Component Nomenclature	HMC	Reason for Replacement	Date	Fuel
27EA0	Augmentor Assy	208	Augmentor Nozzle Mechanism Deterioration	27-Oct-95	JP-8
		156	Afterburner or Augmentor Problem Repair	11-Jun-96	
		156	Afterburner or Augmentor Problem Repair	25-Jul-96	
		156	Afterburner or Augmentor Problem Repair	26-Sep-96	JP-8+100
		156	Afterburner or Augmentor Problem Repair	28-Oct-96	
		156	Afterburner or Augmentor Problem Repair	12-Dec-96	
		303	Damage by Semi-Solid Foreign Object (Birds)	17-Jan-97	
		208	Augmentor Nozzle Mechanism Deterioration	21-Feb-97	
		197	Fuel Leakage	5-Sep-98	
		190	Cracked	6-Sep-99	
		190	Cracked	6-Sep-99	
27EC0	Augmentor Exhaust Nozzle	425	Pitted, Nicked, Chipped, Scored, Scratched, or Crazed	9-Dec-96	JP-8+100
27GAU	Fuel Oil Cooler	223	Control System Component Malfunction	22-Dec-96	JP-8+100

Table 21 Summary of Causes for Flight Aborts January to August, 1996 - Before the JP-8 Test Period

Month	Pilot Reported Discrepancies	Abort Category
Jan	Ground Abort, Engine Nozzle Indicator Inoperative	EEIC (Engine)
	Ground Abort, Engine RPM Decreased for EPU Check (Fuel Flow Stayed Constant)	Eng Perf/Oper
	Ground Abort, Bit Ball Engine MFL-28	EEIC (Engine)
Feb	Ground Abort, No Start - JFS Run Lite, But No Engine RPM	EEIC (Engine)
	Ground Abort, Engine Failed Bit Ball; Engine Malfunction (Performed Sec Check While Doing FLCS Check)	Pilot error
	Ground Abort, Inlet Icing System Overly Sensitive - Light Kept Coming On	EEIC (Engine)
	Air Abort, Engine Bit Ball	EEIC (Engine)
	Ground Abort, Engine Fired On Start, Engine Slow To Light	Eng Perf/Oper
	Ground Abort, Augmentor Would Not Light	Eng Perf/Oper
Mar	Air Abort, 1st Flight Engine PLF	Fuel (Engine)
Apr	Ground Abort, After Engine Start, Engine Accelerated to 80% With Nozzle At 35%	EEIC (Engine)
May	Ground Abort, Pilot Inadvertently Placed Throttle in Prior to Start Causing Abort (Replaced Engine Igniter)	Pilot error
	Ground Abort, Engine No Start	Mech/Hyd (Engine)
	Ground Abort, EMSC Bit Ball	EEIC (Engine)
June	Air Abort, On Takeoff EGT Rose To 935 Degrees (Replaced FTIT Indicator)	EEIC (Engine)
	Ground Abort, Multi Engine Cautions On Downloads	EEIC (Engine)
Aug	Ground Abort, No RPM Increase After Throttle Moved To 20% (Ops Check Good)	Eng Perf/Oper

Table 22 Summary of Causes for Flight Aborts September 1996 to December 1997 - <u>During</u> the JP-8 Test Period

Month	Pilot Reported Discrepancies	Abort Category
Sep 96	Ground Abort, Engine Nozzle Closed (Replaced AFT Control)	EEIC (Engine)
	Ground Abort, Engine Bit Ball Regulator Power Fault	EEIC (Engine)
Oct	Ground Abort, Engine Surged Slightly (Replaced Pyrometer)	EEIC (Engine)
Nov	Air Abort, Loud Noise Under Seat and Vibration (Inspected Metal Detector, Found Metal and Brass Flakes In Oil)	Mech/Hyd (Engine)
Dec	Ground Abort, EMSC Bit Ball Low Battery(Installed New EMSC Battery)	EEIC (Engine)
	Air Abort, Multiple Bird Strike Around Intake Area	Bird Strike
Jan 97	Air Abort, Smoke and Fumes In Cockpit	Fire/Smoke
Feb	Ground Abort, Engine No Start (Ignition Exciter Replaced)	EEIC (Engine)
Mar	Ground Abort, No Anti-Ice Fault 1-12	EEIC (Engine)
Apr	Ground Abort, Engine Auto Transfer To SEC When Exhaust Does Not Respond To Engine Demand	Mech/Hyd (Engine)
May	Air Abort, IFE Oil Pressure Stabilized at 28 PSI At All Throttle Settings (Replaced W-8 Cable)	EEIC (Engine)
Jun	Ground Abort, FTIT Gage Inoperative (Replaced Gage)	EEIC (Cockpit)
Jul	Air Abort, Engine Oil Pressure Fluctuation (Replaced Oil Pressure Indicator)	EEIC (Engine)
	Ground Abort, Engine MFL 062 Bit Ball *(Replaced AFT Control)*	EEIC (Engine)
Aug	Ground Abort, (Repaired Wire In Clutch Servo Cannon Plug)	Mech/Hyd (Access)
	Ground Abort, FTIT Gage Inoperative (Cannon Plug Dirty, Cleaned Cannon Plug	EEIC (Engine)
	Ground Abort, Overheat Detection Test (Tighten Loose Connector, Ops Check Good)	EEIC (Engine)
	Ground Abort, FTIT Gage Inoperative (Replaced Probe and Sensor)	EEIC (Engine)
Sep	Ground Abort, ADG Filter pin Popped (Replaced ΔP Indicator and ADG Filter)	?
	Ground Abort, Nozzle Indicated 10% Open In Sec Idle (Replaced LVDT)	EEIC (Engine)
Oct	Ground Abort, FCC Failed (Target Identification Set Laser)	Weapons
	Air Abort, Noticeable Engine and Airframe Vibration(Removed Engine For Investigation)	Mech/Hyd (Engine)
	Air Abort, Noticeable Engine and Airframe Vibration (Removed Noticeable Vib with Throttle at 88-92% (Engine Systems)	Mech/Hyd (Engine)
	Ground Abort, Left Brake Leaking	Mech/Hyd (Airframe)
	Ground Abort, Engine RPM Fluctuation With Engine In Secondary Mode (Replaced Main *Engine Control*)	EEIC (Engine)
	Ground Abort, Engine RPM Fluctuation With Engine In Secondary Mode (Replaced Main *Engine Control*)	EEIC (Engine)
	Ground Abort, Left Wing Leaking Under Pressure	Fuel (Airframe)
	Ground Abort, N/W/S Would Not Engage	Mech/Hyd (Airframe)

Table 22. Summary of Causes for Flight Aborts September 1996 to December 1997 - During the JP-8 Test Period (Concluded)

Month	Pilot Reported Discrepancies	Abort Category
Nov 97	Ground Abort, Rear Cockpit Eyebrow Missing	Mech/Hyd (Airframe)
	Ground Abort, HUD Inoperative	EEIC (Cockpit)
	Air Abort, Equipment Hot Light Illuminated 5 Minutes Into Flight	EEIC (Cockpit)
	Ground Abort, Oil Pressure Pegged at 85-90 PSI for 5 Minutes Before Coming Into Normal Range	Mech/Hyd (Engine)
	Air Abort, Standby Generator Failed 10 Minutes After Takeoff	EEIC (Accessories)
	Ground Abort, Oil Pressure Pegged at 90 PSI For 3 Minutes After Start	Mech/Hyd (Engine)
	Ground Abort, Engine Bit Ball EMSC Low Battery	EEIC (Engine)
	Ground Abort, FCC Failed (Target Identification Set Laser)	Weapons
	Ground Abort, RCP Pilot Could Not Transmit On UHF	EEIC (Cockpit)
Dec	Ground Abort, Main Generator Would Not Com On Line	EEIC (Accessories)
	Ground Abort, ADC Light Came On	EEIC (Computer)
	Air Abort, C/Line Fuel Tank Would Not Feed	Fuel (Airframe)
	Ground Abort, Main Generator Would Not Come On	Mech/Hyd (Accessories)
	Ground Abort, Engine Bit Ball After Start	EEIC (Engine)
	Flight Abort, Main Generator Failed	Mech/Hyd (Access)
	Ground Abort, ADG Filter pin Popped After Engine Start	APU
	Ground Abort, Engine Bit Ball Found After EPU Check	EEIC (Engine)
	Ground Abort, Equipment Hot Light After Start	EEIC (Cockpit)
	Ground Abort, Main Generator Failed	Mech/Hyd (Access)
	Ground Abort, DED Interm. Went Off and On For No Reason	Weapons
	UFC Laser Brite Fades In and Out	Weapons
	Ground Abort, Engine Started But Went Immediately to 80-84% RPM Fluctuation Nozzle	Mech/Hyd (Engine)

Table 23 Summary of Causes for Flight Aborts January to December 1998 - During the JP-8 Test Period

Month	Pilot Reported Discrepancies	Abort Category
Jan	Ground Abort, Equipment Hot Light After Start	EEIC (Cockpit)
	Ground Abort, Engine No Start	APU
	Ground Abort, Right Brake Leaking.	Mech/Hyd (Airframe)
	Ground Abort, FMS 004 MFL	Mech/Hyd (Airframe)
	Ground Abort, FLCS Amber "D" Light On When Running	EEIC (Computer)
	Ground Abort, MFD'S Cycles On and Off	EEIC (Cockpit)
	Air Abort, After Takeoff After Burner Was Late To Light	Engine Malfunction
	Ground Abort, Hud Fail. MFL068.	EEIC (Cockpit)
	Ground Abort, Aircraft Ingested Paper On The Ramp	FOD
Feb	Air Abort, Elec Power Surges Through MFDS Recyling DId Not Clear	EEIC (Cockpit)
	Ground Abort, Anti-Skid Fail On Takeoff Roll	Mech/Hyd (Airframe)
	Ground Abort, Left Vertral Fin Damaged Beyond Repair	Mech/Hyd (Airframe)
	Ground Abort, Main Gen Fail.	EEIC (Accessories)
	Ground Abort, Main Gen. Light Never Went Out During Engine Start	EEIC (Accessories)
	Ground Abort, Engine No Start	APU
	Ground Abort, The FLCS Panel Reset Button Was Stuck	EEIC (Computer)
	Ground Abort, FLCS Would Not Self-Test	EEIC (Computer)
	Ground Abort, Oil Pressure Gage Didn't Move During Start	Mech/Hyd (Engine)
	Ground Abort, FLCS Servo Lights Would Not Reset	EEIC (Computer)
Mar	Ground Abort, FLCS Would Not Pass Self Test Step1 Will Not Reset	EEIC (Computer)
	Ground Abort, JFSGround Abort,No Start	APU
	Ground Abort,. Rt. Wing Tank Leaking Fuel From Cap	Fuel (Airframe)
	Ground Abort, Brakes Very Mushey	Mech/Hyd (Airframe)
	Ground Abort, Engine No Start	APU
	Ground Abort, Main Gen. Would Not Come On Line	EEIC (Accessories)
	Ground Abort, No Air Flow In Cockpit, Equipment Hot Lite	EEIC (Cockpit)
	Ground Abort, No Start	APU
	Ground Abort, Main Generator Would Not Come On Line	EEIC (Accessories)

Table 23. **Summary of Causes for Flight Aborts January to December 1998 - During the JP-8 Test Period (Continued)**

Month	Pilot Reported Discrepancies	Abort Category
Mar	Air Abort, External Tanks Wouldn't Feed	Fuel (Airframe)
	Ground Abort FCC Failed After Start Up Plus 2 Min	EEIC (Weapons)
	Ground Abort Engine Nozzle Went Full Closed After Engine Start At Idle	Mech/Hyd (Engine)
	Air Abort, "P" Light On T/O Reset Came On Again When Nose Pulled Up	EEIC (Computer)
	Ground Abort Left Break Failed Intermittly In Ch1	Mech/Hyd (Airframe)
	Ground Abort No Cooling Air In C/P Then Equipment Hot Light Came On	EEIC (Cockpit)
	Ground Abort Pilot Activated EPU, Put Power In Batt	APU
	Ground Abort JFS Clutch Servo Never Engaged After JFS Start	APU
Apr	Ground Abort, FFP Light Intermittent	Fuel (Airframe)
	Ground Abort, MFD's Failed Several Times On Grnd	EEIC (Weapons)
	Air Abort, Ife. Equip Hot Light Came On 20 Minutes Into Flt	EEIC (Cockpit)
	Ground Abort, Eng Bit Ball, Emsc Bus Fail	Mech/Hyd (Engine)
	Ground Abort, T/O and Landing Config Light On With Movement	Mech/Hyd (Airframe)
	Ground Abort, Equip Hot Light On Ground. Went Off When Turned FCR Off	EEIC (Cockpit)
	Ground Abort, Pressure Line In Right Wheel Well Leaking At Elbow	Mech/Hyd (Airframe)
	Ground Abort, No Airlfow At All Through Mask/System	EEIC (Cockpit)
	Ground Abort, MFD Bus	EEIC (Weapons)
	Ground Abort, Several Sms MFL's, Left Wing Not Responding To SMS	EEIC (Weapons)
	Air Abort, On Takeoff-Oil Press Was OK After Selecting The Oil Press	Mech/Hyd (Engine)
	Ground Abort, Totalizer On Fuel Gage and DED Showed 1k To 3k Low	EEIC (Airframe)
	Ground Abort, INSBus Fail - Three Attempts	EEIC (Weapons)
	Ground Abort, No Oil Pressure On Oil Pressure Indicator	Mech/Hyd (Engine)
May	Air Abort, Ife, Compressor Stall In Flight, Climbing Thru 12000ft 300kts	Mech/Hyd (Engine)
	Ground Abort, Fuel Flow At Idle Showed Between 400-500 pph	Fuel (Engine)
	Ground Abort, Hyd Oil Pressure Light Inop	EEIC (Cockpit)
	Ground Abort, FFP Boost Light Flickers At Idle	EEIC (Airframe)
	Ground Abort, Nose Wheel Steering Fail Light Replaced	Mech/Hyd (Airframe)
	Air Abort, Fuel Indicator Needle and Totalizer Were Erratic	Fuel (Engine)

Table 23. **Summary of Causes for Flight Aborts January to December 1998 - During the JP-8 Test Period (Continued)**

Month	Pilot Reported Discrepancies	Abort Category
May	Ground Abort, Aircraft Would Not Start	APU
	Ground Abort, FCR 109 MFL (FCR Fail) and Equip Hot Light Would Light W/Radar	EEIC (Cockpit)
	Ground Abort, INUWould Not Align, INU Bus Fail	Weapons
	Ground Abort, While Taxing- Brakes Failed Followed By Anti-Skid Light	Mech/Hyd (Airframe)
	Ground Abort, EPU Will Not Self Test	APU
	Ground Abort, MFL052 Eng	Mech/Hyd (Engine)
	Ground Abort, Engine Bit Ball After Start. MFL FDR 011	EEIC (Engine)
	Ground Abort, Engine MFL032 AB No Light	EEIC (Engine)
	Air Abort, FMS 004 and FDR 044. Needles Went To 400#	Fuel (Engine)
	Ground Abort, Engine MFL GEE054, No Go Bit Ball,	Mech/Hyd (Engine)
	Ground Abort, INS W/Not Come On Line At All, Cycled Full Power 3 Times	EEIC (Weapons)
	Ground Abort, On Engine Start Up Got Bit Ball, Engine Idle 83%	Mech/Hyd (Engine)
	Air Abort, To/LNG Config. Light Came On In Flt With Gear Up At 500kt/1800ft]	EEIC (Computer)
Jun	Air Abort, Landing Gear Failed To Retract. Gear Handle Wouldn't Come Up	Mech/Hyd (Airframe)
	Air Abort, Comm Access Panel Open In Flight	Mech/Hyd (Airframe)
	Ground Abort Before Flt No Engine Start	APU
	Ground Abort, No Start	APU
	Ground Abort, HUD Failed MFL068 and HUD Degraded In Pfl- Would Not Reset	Weapons
	Ground Abort, Engine No Start	APU
	Ground Abort, HUD Failed MFL 068 and HUD Degraded In Plf	EEIC (Cockpit)
	Ground Abort, No Start On 1 Or 2	APU
	Ground Abort, Throttle Popped Out Of Gate -	Mech/Hyd (Cockpit)
Jul	Ground Abort, UFC In-Operative (ICP Bad)	EEIC (Weapons)
	Ground Abort, FLCS Self Test Kept Stopping At 37	EEIC (Computer)
	Ground Abort, Pilot Found Bird In Intake During Walk Around Inspection	FOD
	Ground Abort, Lt Brake In Channel 1 At Taxi Speed	Mech/Hyd (Airframe)
	Ground Abort, FMS 004 MFL - APG Removed	Fuel (Engine)
	Ground Abort, Anti-Skid Switch Light While Taxing	Mech/Hyd (Airframe)

Table 23. Summary of Causes for Flight Aborts January to December 1998 - <u>During</u> the JP-8 Test Period (Continued)

Month	Pilot Reported Discrepancies	Abort Category
Jul	Ground Abort, Anti Skid Light Anti Skid Failed During Taxi	Mech/Hyd (Airframe)
	Ground Abort, No FTIT At Eng Start-T-5.6 Thermocoupler Tip Missing	EEIC (Engine)
Aug	Air Abort, Multiple Bird Strikes On Takeoff. No Other Problems	Mech/Hyd (Airframe)
	Ground Abort, Failed FLCS Step 45	EEIC (Computer)
	Ground Abort, Anti Skid Light Taxing at 15 Knots	Mech/Hyd (Airframe)
	Ground Abort, Equip Hot Light - Bad Turbine	EEIC (Cockpit)
	Ground Abort, FLCS Failed Horiz. and Rudder At 41 & 43	Mech/Hyd (Airframe)
	Ground Abort, FLCS Fails Step 19	Mech/Hyd (Airframe)
	Ground Abort, A System Hyd Transmitter Bad	Mech/Hyd (Airframe)
	Ground Abort, Shoulder Straps Inop	Mech/Hyd (Cockpit)
	Ground Abort, FCCFail	EEIC (Computer)
	Ground Abort, FCCFail	EEIC (Computer)
	Ground Abort Left Main Tire Blown At EOR	Mech/Hyd (Airframe)
	Ground Abort, Anti-Skid Failed.	Mech/Hyd (Airframe)
	Ground Abort, Canopy Fails To Go Up and Down	Mech/Hyd (Cockpit)
Sep	Ground Abort, Anit Skid Failed On Taxi	Mech/Hyd (Airframe)
	Ground Abort, Eng Bit Ball 052	EEIC (Engine)
	Ground Abort, Ems Fault With A Bit Ball Immediately After Engine Start	EEIC (Engine)
	Ground Abort, Rt Flaperon In-Op When Flt Controls Cycled On JFS Run	EEIC (Cockpit)
	Ground Abort, When Flight Controls Are Cycled, System Pressure Drops	Mech/Hyd (Airframe)
	Ground Abort, NWS Fail Light Illum. 8 Min. After Engine Start	Mech/Hyd (Airframe)
	Ground Abort, N/W/S Fail Light Replaced	Mech/Hyd (Airframe)
	Ground Abort, FLCSMal Light At 45, Attempted 5 Tests	EEIC (Computer)
	Ground Abort, JFS No Start	APU
	Ground Abort, FLCS S/Test Malfunction At Step 4 With Lower Left Ind Light	EEIC (Computer)
Oct	Ground Abort, Main Generator Fail Prior To Taxi,	EEIC (Accessories)
	Ground Abort, After Start FLCS Panel Would Not Cl	EEIC (Computer)
	Ground Abort, Excessive Oil In Sihgt Gage After	Mech/Hyd (Engine)

Table 23. Summary of Causes for Flight Aborts January to December 1998 - During the JP-8 Test Period (Continued)

Month	Pilot Reported Discrepancies	Abort Category
Oct	Ground Abort, Both Radios Squealed	EEIC (Cockpit)
	Ground Abort, Left Flaperon Would Not Reset	EEIC (Cockpit)
	Ground Abort, EPUWould Not Run During Grnd Check	APU
	Ground Abort, Neither Main Or Standby Gens Came On-Line After Start	EEIC (Accessories)
	Ground Abort, FLCS "R" Light Would Not Clear After Servo/Elect Reset	EEIC (Cockpit)
	Ground Abort, Main Generator Failed	EEIC (Accessories)
	Ground Abort, "B" Sys. Hyd. Pump Case Drain Leaking	Mech/Hyd (Airframe)
	Ground Abort, No Power Indications Before Start	EEIC (Accessories)
	Ground Abort, Flcs "D" Brnch Power Light Fails To Illuminate	EEIC (Airframe)
	Ground Abort, Rt Fuel Resevoir Was Between 200-250 lbs	Fuel (Airframe)
	Ground Abort, Canopy Will Not Close	Mech/Hyd (Cockpit)
	Ground Abort, Excessive Hyd. Leak From Case Drain	Mech/Hyd (Airframe)
	Ground Abort, EMSC Bit Ball Downloaded 2x But Came Back No Faults	EEIC (Engine)
	Ground Abort, EMSC Battery Dead	EEIC (Engine)
Nov	Ground Abort Before Taxi Equipment Hot Light	EEIC (Cockpit)
	Ground Abort, At EOR Rt Flaperon Went Full-Down To Full-Up By Itself	EEIC (Cockpit)
	Ground Abort, Eng Bit Ball 017 Had Caution Light Eng	EEIC (Engine)
Dec	Ground Abort, Left Brake Leaking	Mech/Hyd (Airframe)
	Ground Abort, FCCFailure W/Not Reset No Off Loaded For AC	Weapons
	Ground Abort, B Sys Hyd Fluc 2000/3000psi Settled At 3200-Outside Gage At 0	Mech/Hyd (Airframe)
	Ground Abort, No Batt Power	EEIC (Accessories)
	Ground Abort, Ffp Light Inop	EEIC (Airframe)
	Ground Abort, Lt Brake Leaking	Mech/Hyd (Airframe)
	Ground Abort, Intercom Inop	EEIC (Cockpit)
	Ground Abort, Cockpit Air Temp Control Sys	EEIC (Cockpit)
	Ground Abort, Small Hyd Leak Detected At Last Chance	Mech/Hyd (Airframe)
	Air Abort, Trapped Fuel Warning In Hud. Tank Showed Feeding	Fuel (Airframe)
	Ground Abort, Excessive Discharge Press. From Left Underwing Vent	Fuel (Airframe)

Table 23. Summary of Causes for Flight Aborts January to December 1998 - During the JP-8 Test Period (Concluded)

Month	Pilot Reported Discrepancies	Abort Category
Dec	Ground Abort, Hyd Leak In 3rd Drain Lt Wheel Well	Mech/Hyd (Airframe)
	Ground Abort, UHF Inop	EEIC (Cockpit)
	Air Abort, Landing Gear Overspeed (310kcas)	Mech/Hyd (Airframe)
	Ground Abort, No FFP Light	Fuel (Airframe)
	Ground Abort, Fuel Pump #6 Intermittent FFP Not	Fuel (Airframe)
	Gr-Air Abort, IFE Upon Gear Retraction The Red Light In Gear	Mech/Hyd (Airframe)

Table 24 Summary of Causes for Flight Aborts January to September 1999 - During the JP-8 Test Period

Month	Pilot Reported Discrepancies	Abort Category
Jan	No Flt Grnd Abort, Aft Fuel Low Light On. Fuel Qty's Normal	EEIC (Cockpit)
	No Flt Grnd Abort, Anti Skid Light Illuminated During Taxi	EEIC (Cockpit)
	No Flt Grnd Abort, Batt Fail Light	EEIC (Cockpit)
	Air Abort, Cabin Pressure Did Not Keep On Schedule. Cockpit	Mech/Hyd (Cockpit)
	No Flt Grnd Abort, During Grnd Chk Of EPU, Acft Vented Fuel Out Of Left Wing	Fuel (Airframe)
	Air Abort, External Tanks Feed Intermittently	Fuel (Airframe)
	No Flt Grnd Abort, ECS Surging After Start and Equip	EEIC (Engine)
	Air Abort, FLCS 'P' Light On Just After Rotation, Would No Reset	EEIC (Computer)
	No Flt Grnd Abort, FCC Failed After Start With MFL 149. Smelled Burn Fumes In Cockpit	Smoke/Fumes
Feb	No Flt Grnd Abort, FFP Light Flashing In Idle and Throttle Up Position	Fuel (Airframe)
	Air Abort, IFE - Stby Gen Fail In Flight. No Elec System Malfunction	EEIC (Accessories)
	No Flt Grnd Abort, FLCS	EEIC (Computer)
	No Flt Grnd Abort, FLCS Batt B Light Will Not Illuminate During Self Test	EEIC (Computer)
	No Flt Grnd Abort, FLCS Failed Self Test At Step 48	EEIC (Computer)
	No Flt Grnd Abort, FLCS Fails Step 4 With P Light	EEIC (Computer)
	No Flt Grnd Abort, Main Gen. Cycled Off For 2-3 Sec After Taxi	EEIC (Accessories)
	No Flt Grnd Abort, No Flight Anti-Skid Lite Illuminated During Taxi	EEIC (Cockpit)
	No Flt Grnd Abort, Nozzle Does Not Move When SEC Selected	Mech/Hyd (Engine)

Table 24. Summary of Causes for Flight Aborts January to September 1999 - During the JP-8 Test Period (Continued)

Month	Pilot Reported Discrepancies	Abort Category
Feb	Air Abort, IFE, Smoke Fumes In Cockpit (Smelled Like Oil Burning)	Smoke/Fumes
	No Flt Grnd Abort, #3 Fuel Boost Pump Inop Press To Test	Fuel (Airframe)
	No Flt Grnd Abort, After Engine Start EFCC Fail	Weapons
	No Flt Grnd Abort, After Engine Start Engine Bitball MFL 052.	EEIC (Computer)
	No Flt Grnd Abort, After Engine Start, Engine Bitball Went Into Sec No MFL's	EEIC (Computer)
	Air Abort, IFE-Oil Pressure Light Came On In Flight	Mech/Hyd (Airframe)
	No Flt Grnd Abort, Air Flow Surged/Stopped As Soon As FCR Turned On	?
	No Flt Grnd Abort, Air Pressure In Cockpit Greatly Reduced	Mech/Hyd (Cockpit)
	Air Abort, INS Total Fail In Flt MFL 011 In Flight Attitude	Weapons
	Air Abort, Lt Main Light Remained On With Red Light In The Handle	EEIC (Airframe)
	No Flt Grnd Abort, Aircraft Battery Dead.	EEIC (Airframe)
Mar	No Flt Grnd Abort, Aircraft Will Not Start	APU
	No Flt Grnd Abort, Anti Skid Failed During Taxi	Mech/Hyd (Airframe)
	No Flt Grnd Abort, Anti-Collision Light Lens Cover Came Off	EEIC (Cockpit)
	Air Abort, Main Gen Fail In Flight After 1 1/2 Flt Time Main Gen Light Illuminated	EEIC (Accessories)
	No Flt Grnd Abort, AOA Off Flag In View	EEIC (Cockpit)
	No Flt Grnd Abort, B Sys Reservoir Vented Overboard Upon Start Up	Mech/Hyd (Airframe)
	No Flt Grnd Abort, Batt Fail Light After Start	EEIC (Airframe)
	No Flt Grnd Abort, Battery Fail Light.	EEIC (Airframe)
	No Flt Grnd Abort, Canopy Actuator Burnt Up	Mech/Hyd (Airframe)
	No Flt Grnd Abort, Eng No Start. A/C Did Not Start On	Engine no start
	No Flt Grnd Abort, Engine No Start, Had Rotation But Starter Would Not Light	EEIC (Engine)
	Air Abort, P Light In Flight. Reset Approx 3 Min Later. P Li	EEIC (Cockpit)
	No Flt Grnd Abort, APU Failed Test	APU
	No Flt Grnd Abort, Equip Hot Light	EEIC (Cockpit)
Apr	No Flt Grnd Abort, FCC Dumped Mfl 149	EEIC (Computer)
	No Flt Grnd Abort, FCC Failed	EEIC (Computer)
	No Flt Grnd Abort, FCCFailed.	EEIC (Computer)

Table 24. Summary of Causes for Flight Aborts January to September 1999 - During the JP-8 Test Period (Continued)

Month	Pilot Reported Discrepancies	Abort Category
Apr	Air Abort, Auto Transfer To Sec In Flight, Eng MFL 051 & 061. Engine Flamed Out On Roll	Engine Flameout
	No Flt Grnd Abort, FCR Fail	EEIC (Computer)
	No Flt Grnd Abort, FCRFailed Mfl FCR 003	EEIC (Computer)
	No Flt Grnd Abort, FCRFailed Prior To Flight FCR Bus FA	EEIC (Computer)
	No Flt Grnd Abort, FCR Kept Cycling.	EEIC (Computer)
	No Flt Grnd Abort, FLCS D Pwr Light Not On & PMG Light Flashing	EEIC (Computer)
	No Flt Grnd Abort, FLCS Failed At Step 50	EEIC (Computer)
	No Flt Grnd Abort, FLCS Failed Step 4.	EEIC (Computer)
	No Flt Grnd Abort, Ftit Gage Inop	EEIC (Engine)
	No Flt Grnd Abort, FTIT Went Past 935 Degrees On Takeoff Roll	EEIC (Engine)
	Air Abort, Bird Strike On T/O Went Through A Flock Of Doves.	Bird Strike
	No Flt Grnd Abort, GAD FLCS Battery Check For A&B.	EEIC (Computer)
	No Flt Grnd Abort, IFE Anti Skid Failed, Pulsating Mode Appeared	Mech/Hyd (Airframe)
May	No Flt Grnd Abort, Left Break Hydraulic Leak.	Mech/Hyd (Airframe)
	No Flt Grnd Abort, Lt Brake Leaking Hyd Fluid	Mech/Hyd (Airframe)
	No Flt Grnd Abort, N.F.G.A FLCS Failed Self Test 47with Y Light Reset & Cyc. Flt Controls	EEIC (Computer)
	No Flt Grnd Abort, No FTIT Indication	EEIC (Engine)
	No Flt Grnd Abort, No FTIT On Gage	EEIC (Engine)
	Air Abort, Birdstrike On Low Approach, Saw 2 Birds, One Hit Canopy Glass	Bird Strike
	No Flt Grnd Abort, No Lt Main Gear Light	EEIC (Airframe)
	No Flt Grnd Abort, Nose Wheel Steering Fail Light	EEIC (Airframe)
	No Flt, Grnd Abort. R Light After Start. Would Not Reset	EEIC (Cockpit)
Jun	No Flt Grnd Abort, O2 Regulator Has Constant Flow	Mech/Hyd (Cockpit)
	No Flt Grnd Abort, On Eng Run-Up To 90% A Series Of Pops and Thuds Were Heard and Felt	Engine
	No Flt Grnd Abort, Right Main Tire Bad	Mech/Hyd (Airframe)
	No Flt Grnd Abort, Rt Flaperon Is Leaking	Mech/Hyd (Airframe)
	No Flt Grnd Abort, U.F.C. Inoperative, Never Came On	Weapons
	No Flt Grnd Abort, UHF Radio - Loud Squeal Continuously With Power On	EEIC (Cockpit)

Table 24. Summary of Causes for Flight Aborts January to September 1999 - During the JP-8 Test Period (Continued)

Month	Pilot Reported Discrepancies	Abort Category
Jun	No Flt Grnd Abort, UHF Radio In-Operative, Recycled Three Times	EEIC (Cockpit)
	No Flt Grnd Abort, #3 Fuel Boost Pump Light Inoperative	EEIC (Cockpit)
	No Flt Grnd Abort, #4 Fuel Boost Pump Light Inoperative	EEIC (Cockpit)
	No Flt Grnd Abort, ADC and LEF Lights Flickered On and Off After Start	EEIC (Cockpit)
	No Flt Grnd Abort, Anti Skid Failed On Taxi	Mech/Hyd (Airframe)
	No Flt Grnd Abort, Antiskid Failed During Taxi Out.	Mech/Hyd (Airframe)
Jul	Air Abort, High Speed Abort Due To Birds Led To Lt Main Tire Fire.	Bird Strike
	No Flt Grnd Abort, Brake Control Channel 2 Inoperative	EEIC (Airframe)
	No Flt Grnd Abort, Centerline Tank Has No Indication.	EEIC (Airframe)
	No Flt Grnd Abort, Data Control Switch Broke Off In Pilot's Hand	Mech/Hyd (Cockpit)
	No Flt Grnd Abort, During Fuel Test Did Not Get A Fwd Fuel Low Light.	EEIC (Cockpit)
	No Flt Grnd Abort, Engine Bit-Ball MFL 052	EEIC (Cockpit)
	No Flt Grnd Abort, Engine MFL 052.	EEIC (Cockpit)
	No Flt Grnd Abort, Engine Rpm Rolled From 72% To 60% Before Reselecting Pri	Engine
	No Flt Grnd Abort, EPU Light Flickered Then Went Out.	EEIC (Cockpit)
	No Flt Grnd Abort, FCRFailed , FCR 232 MFL	EEIC (Cockpit)
	No Flt Grnd Abort, FFP Light Inoperative	EEIC (Cockpit)
	No Flt Grnd Abort, FLCS Failed Bit Check 44 3 Times.	EEIC (Computer)
	No Flt Grnd Abort, FLCS Self Test Failed 3 Times At	EEIC (Computer)
	No Flt Grnd Abort, Flight Left Main Landing Gear Brake Leaking	Mech/Hyd (Airframe)
Aug	No Flt Grnd Abort, Fuel Totalizer Went From 8800 To	EEIC (Airframe)
	No Flt Grnd Abort, L.E.F Light Off	EEIC (Cockpit)
	Air Abort, IFE Light Came On In Conjunction With Gear Up.	Mech/Hyd (Airframe)
	No Flt Grnd Abort, Lt Brake Failed During Taxi.	Mech/Hyd (Airframe)
	No Flt Grnd Abort, Main Fuel Filter Bypass Indicator Popped Aft.	Fuel (Airframe)
	No Flt Grnd Abort, Missile Detent Bad	Weapons
	Air Abort, Right Main Gear Door Did Not Close.	Mech/Hyd (Airframe)
	No Flt Grnd Abort, On Taxi, Roll Out NWS Failed On Rt Turn	Mech/Hyd (Airframe)

Table 24. Summary of Causes for Flight Aborts January to September 1999 - During the JP-8 Test Period (Concluded)

Month	Pilot Reported Discrepancies	Abort Category
Aug	No Flt Grnd Abort, Rpm Gage Went To Zero (F/C/P)	EEIC (Cockpit)
	No Flt Grnd Abort, Rt Brake Leaking, Found In Arming Area	Mech/Hyd (Airframe)
Sep	No Flt Grnd Abort, Standby Gen Fail During/After EPU Ck.	EEIC (Accessories)
	No Flt Grnd Abort, Trapped Fuel Light.	Weapons
	No Flt Grnd Abort, VHF Radio Inop Couldn't Recieve	EEIC (Cockpit)
	No Flt Grnd Abort, APU Did Not Cycle	APU
	No Flt Grnd Abort, Fuel Leak Rt Top Wing Around Falcon Up Plate	Fuel (Airframe)
	No Flt Grnd Abort, Lt Servo Light Would Not Reset	Mech/Hyd (Airframe)
	Air Abort, SOF Noticed Fuel Venting On Takeoff.	Fuel (Airframe)
	No Flt Grnd Abort, Lt Horizontial Servo Light Would Not Go Out	Mech/Hyd (Airframe)
	No Flt Grnd Abort, Ox Knob Came Off R2 02 Regulator	Mech/Hyd (Cockpit)
	No Flt Grnd Abort, Smoke In Cockpit	Smoke/Fumes

End of JP-8+100 evaluation. Unit transferred to Wright-Patterson AFB and began using JP-8.

Table 25 Summary of Causes for Flight Aborts October 1999 to March 2000 - After Returning to JP-8 Following Test Period

Month	Pilot Reported Discrepancies	Abort Category
Oct	No Flt Ground Abort A/C Batt Dead	EEIC (Airframe)
	No Flt Ground Abort Hyd Fluid Leaking Eng Bay Area	Mech/Hyd (Engine)
	No Flight, Ground Abort, Lt Brake Leaking	Mech/Hyd (Airframe)
	No Flight, Ground Abort, ECS Surged and Eventually Shut Down	EEIC (Computer)
	No Flight, Ground Abort, Engine Nacelle Has No Airflow.	?
	No Flight Ground Abort UFC Would Not Work Or Any Master	Weapons
	No Flight Grnd Abort, HUD Inop	EEIC (Cockpit)
	No Flt Ground Abort Main Fuel Filter Bypass Indicator Extend	Fuel (Engine)
	No Flt Ground Abort Main Fuel Filter Bypass Indicator Extend	Fuel (Engine)
	No Flight, Ground Abort. Loss Of Thrust During Takeoff	Mech/Hyd (Engine)
	No Flight Ground Abort Auto Transfer To Sec On T/O Roll Around	Mech/Hyd (Engine)

Table 25. Summary of Causes for Flight Aborts October 1999 to March 2000 - After Returning to JP-8 Following Test Period (Continued)

Month	Pilot Reported Discrepancies	Abort Category
Oct	No Flt Grnd Abort CADC Fail	EEIC (Cockpit)
	No Flt Grnd Abort Lt Brake Quit, No Anti Skid Lights	Mech/Hyd (Airframe)
	No Flt Grnd Abort FLCS Fails Step16	EEIC (Computer)
	No Flight, Ground Abort, Got 'R' Light 2 Times During Flight	EEIC (Cockpit)
Nov	No Flight Ground Abort FFP Light Flickers Above Idle	Fuel (Airframe)
	No Flt Ground Abort #3 Boost Pump Inop. Bulb Check Good Eng	Fuel (Airframe)
	No Flight Ground Abort Lt Ventral Fin Cracked	Mech/Hyd (Airframe)
	No Flt Grnd Abort C/L Tank Leaking From Aft Seam	Fuel (Airframe)
	No Flt Grnd Abort Boost Pump #4 Light Inop	EEIC (Cockpit)
	When Fcr Was Turned On Had Equipment Hot Light.	EEIC (Cockpit)
	Partial Electrical Failure, Master Caution Light On ADC	EEIC (Airframe)
	No Flight, Ground Abort, UHF Radio In-Operative	EEIC (Cockpit)
	No Flt Grnd Abort No Start	APU
Dec	No Fligt Ground Abort Ffp Light Flickers	Fuel (Airframe)
	No Flight Grnd Abort HUD Totally Inop No MFLS Fwd/Aft Ck Pt	EEIC (Cockpit)
	Air Abort Centerline Tank Wouldn't Feed	Fuel (Airframe)
	No Flight, Ground Abort, Center Line Tank Reads Zero,	Fuel (Airframe)
	No Flight Ground Abort Hung Start @ 45%	?
	Flcs Wouldn't Advance Past Step4	EEIC (Cockpit)
Jan	Eng Rpm Indicator Flux	EEIC (Cockpit)
	No Flight Grnd Abort Ins Batt Fail Warn MFL 029 Came On During	EEIC (Airframe)
	Rpm Gage Dropped To Approx 25% Then Back To 85% Got Eng	EEIC (Cockpit)
	No Flight, Ground Abort, Vhf Receiver Is In-Op. Transmitt	EEIC (Cockpit)
	Rpm Gage Flutuations	EEIC (Cockpit)
	Air Abort Standby Generator Failed In Flt Would Not Reset	EEIC (Generator)
	No Flt Gnd Abrt Shortly After Both Gens Came On Line After	EEIC (Generator)
	Cadc 003 MFL No Reset Failed Step 4 Of FLCS Bit	EEIC (Cockpit)
	No Flight,Ground Abort, Pilot Had FLCS Pmg Light	EEIC (Computer)
	No Flight Ground Abort Main Gen Did Not Come On Line At	EEIC (Generator)

Table 25. Summary of Causes for Flight Aborts October 1999 to March 2000 - After Returning to JP-8 Following Test Period (Concluded)

Month	Pilot Reported Discrepancies	Abort Category
Feb	No Ground Abort Main Gen Did Not Come On Line At Start Up	EEIC (Generator)
	Eng No Start Forward Cart Bypass	EEIC (Accessories)
	No Flight Ground Abort NWS Fail Caution Lite Came On During	Mech/Hyd Airframe)
	No Flight, Ground Abort, After Engine Start Had Main	EEIC (Generator)
	Nose Landing Gear Door Would Not Close. Had Light In Gear	Mech/Hyd (Airframe)
	Eng Fault Light Illum At AB Termination In 2-3 G Right Turn	Engine (Combustion)
Mar	No Flight Ground Abort Main Gen Light Stayed On After Eng Start	EEIC (Generator)
	Fuel Indic Prob. Totalizer & Both Fuel Needles Indic. Zero	Fuel (Airframe)
	No Flight, Ground Abort, Engine Bleed Air Nacelle Ejector	Mech/Hyd (Airframe)
	No Flight Ground Abort Hyd Leak (Possible B Sys Pump).	Mech/Hyd (Airframe)
	No Flight Ground Abort FFP Light Flickered At Idle and At	Fuel (Airframe)
	No Flight, Ground Abort, Lt Brake, Channel 1 Quit During	Mech/Hyd (Airframe)
	No Flight Ground Abort Anti-Skid Failed Twice While Taxi	Mech/Hyd (Airframe)
	FCC Fail 149 FCR Fail 116 Restart Still Did Not Work	Weapons
	No Flight Ground Abort, SMS 080	Weapons
	At 90% Pwr Just Before Brake Release FCC Fcr Rwr HUD All Fail	EEIC (Cockpit)
	No Flight, Ground Abort, FCC Failed. Had FCC 149 MFL and FCC	EEIC (Cockpit)
	No Flight, Ground Abort, UHF Radio Inoperative	EEIC (Cockpit)

Unscheduled Maintenance Actions on Tracked Items

Detailed data on unscheduled maintenance actions are provided in the Tables. Tables 17, 18, and 19 are calendars of the incidents for the three reporting periods. Table 20 is a summary of the causes for the maintenance actions. Of the 19 items tracked, all but 4 were involved in unscheduled maintenance either before, during, or after the test period.

Figure 29 is a historical summary of these actions for all engines in the program. Figure 30 presents a historical summary of the costs associated with these maintenance actions; included are both the cost of the item and the associated labor requirements for replacing it. During the 23-month historical period operating on JP-8, there were 78 unscheduled maintenance actions on the tracked items, with an associated cost of $1.67M. During the 37-month test period itself, there were only 67 unscheduled maintenance actions with an associated cost of $1.57M. In the six-month period when the 178th returned to using JP-8, there were seven unscheduled maintenance actions with an associated cost of $147,000.

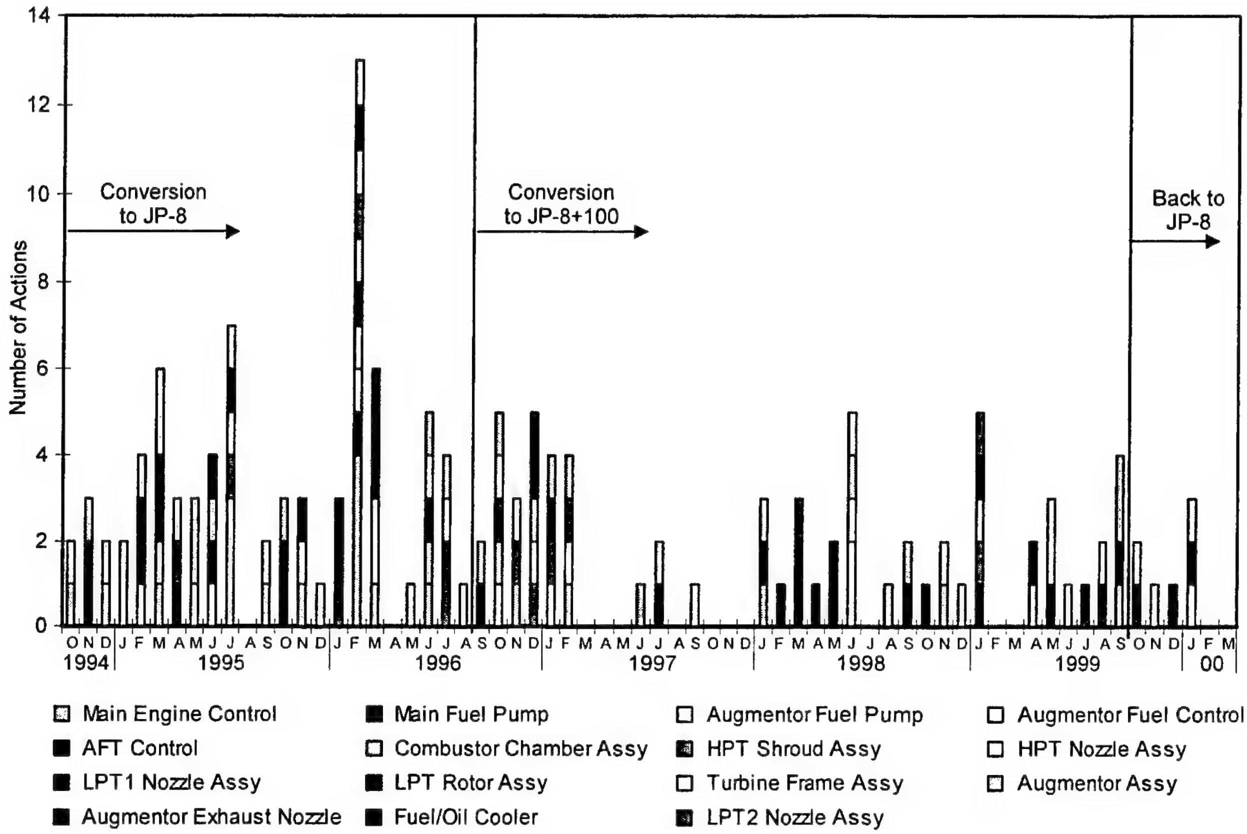


Figure 29 Historical Summary of Unscheduled Maintenance Actions

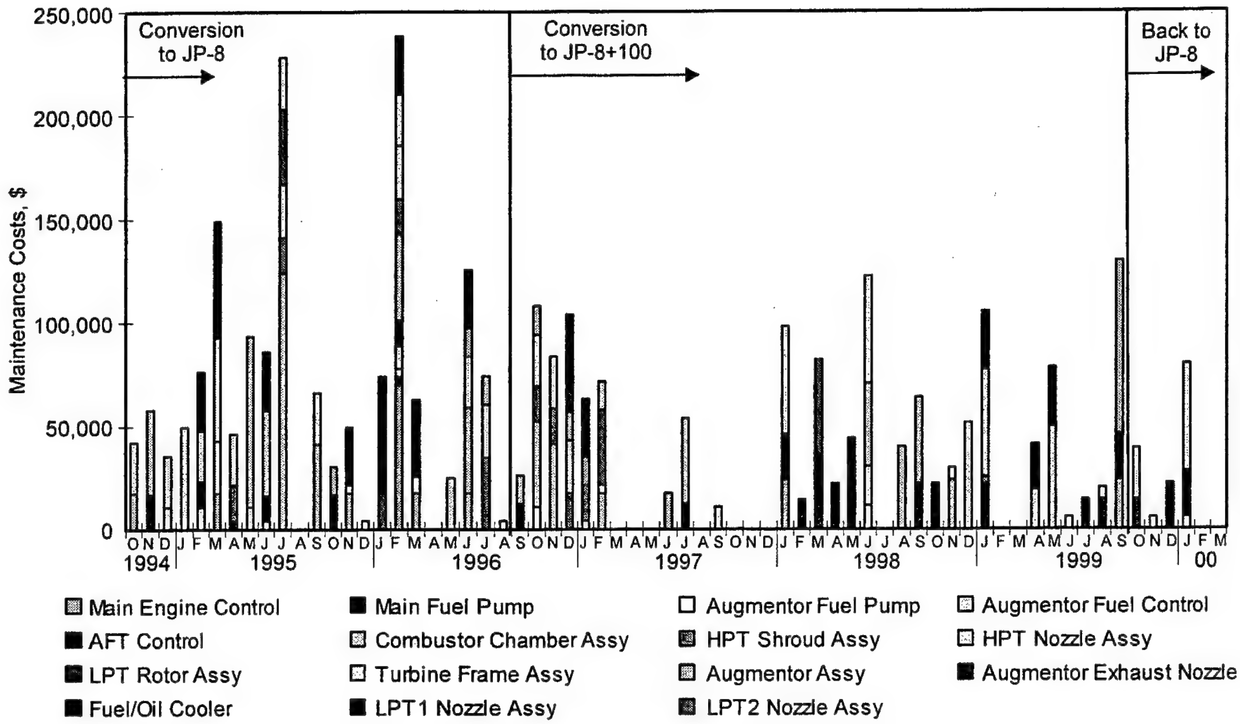


Figure 30 Historical Summary of Costs of Unscheduled Maintenance of Tracked Items

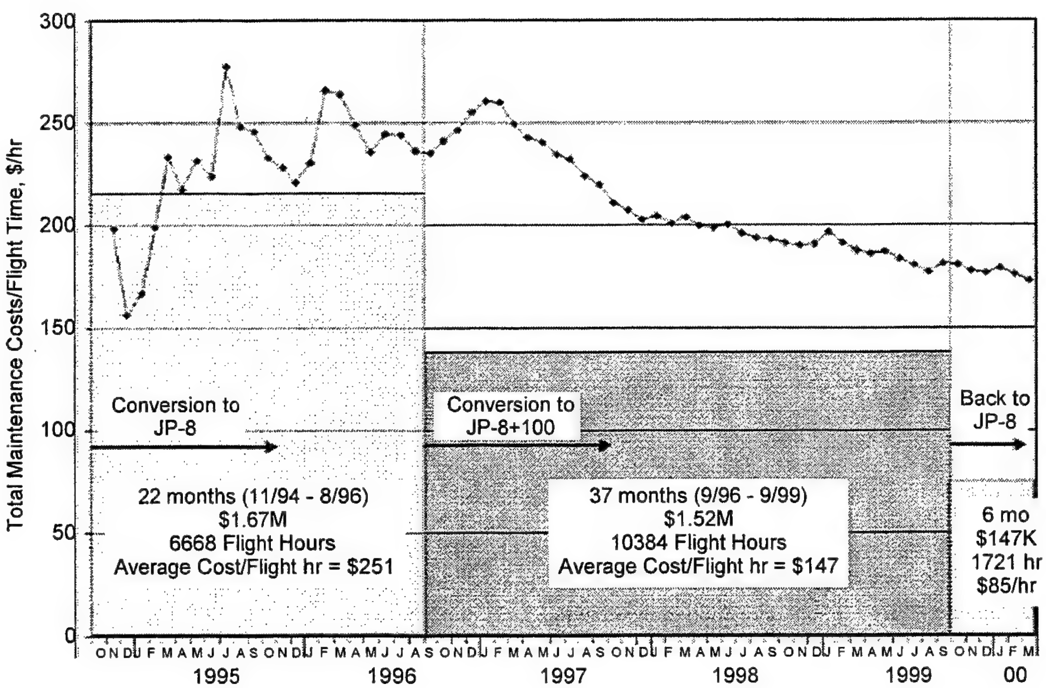


Figure 31 Average Maintenance Costs Per Flight Hour

Figure 31 combines these data to show the history of the cost per flight hour associated with the unscheduled maintenance of the tracked items. (Note: This is not the maintenance cost per flight hour on these engines/aircraft.) Figure 4 shows that, during the JP-8 historical period, there was a steady increase in maintenance costs per flight hour; then, about six months after switching to JP-8+100, maintenance costs began a steady downward trend that continued into the six-month posttest period on JP-8.

These results suggest that the use of JP-8+100 would result in about a 40% reduction in maintenance costs for the tracked items. However, not all of the reductions in unscheduled maintenance can be attributed to the use of JP-8+100. It was expected that the use of JP-8+100 would primarily reduce hot-section maintenance to address the effects of hot streaks. The tracking of fuel system components was to identify any possible deleterious effects of using JP-8+100. For example, the reduction in the replacement of main-engine fuel controls was due to the modification of a design defect. It is therefore useful to divide the tracked items into two categories:

- Hot-section components, for which the use of JP-8+100 might reduce maintenance by reducing fuel-nozzle fouling and hot streaks
- Fuel system components, such as controls and pumps, to determine if using JP-8+100 had any deleterious effects

It is also useful to further divide these into the major causes for maintenance — those that can be related to fuel and combustion and those that cannot, based on the descriptions in the maintenance data base. Table 26 lists the generalized causes for unscheduled replacement of hot-section components according to the three analysis periods. With a very few exceptions, the causes given for replacement fell into three categories:

1. *Combustion damage* including hot spots and burn-throughs
2. *Pitted, nicked, chipped, scored, scratched,* or *crazed* (these were termed "noncombustion")
3. *Cracked,* which may have been due to mechanical or thermal stresses

"Combustion damage" would most likely be affected by JP-8+100 through reduced fuel-nozzle fouling and resultant hot streaks. Between the historical JP-8 period and the JP-8+100 test period, there was a significant reduction in the combustion-related replacement of combustion chambers and turbine frame assemblies, and to a lesser extent LPT1 nozzle assemblies and HPT shroud assemblies. For the other items there were either no combustion-related actions or the difference was felt to be insignificant. There were only two maintenance actions on hot section items during the six-month period after returning to JP-8, and for all practical purposes these have no bearing on the discussion.

Table 27 presents a model for potential cost savings by taking the cost per flight hour for JP-8 historical period, based on the total maintenance cost for each item and the total hours flown in that period, and scaling that figure by the number of hours flown during the JP-8+100 test period to get the extrapolated maintenance cost had the maintenance rate remained the same. The difference between this extrapolated cost and the real cost for repairing that item during the JP-8+100 period represents a potential cost savings due to using JP-8+100, all else being equal. The result shows that the 178th FG saved as much as \$1.3M during the 37 months they flew on JP-8+100 due to reduced maintenance costs. Whether all of this savings was due to the use of JP-8+100 is open to question.

The engine maintenance personnel of the 178th FG believe the major reason that hot-section maintenance costs went down was because the engines were in much better maintenance condition during the JP-8+100 evaluation period rather than due to the fuel change. Discussions with the 178th engine maintenance personnel revealed that when they received the engines from the active Air Force, the engines were "worn out and in poor condition," that is, the maintenance condition of the hot sections was poor. They finished refurbishing the engines shortly after the JP-8+100 test program was initiated.

Table 26 Generalized Summary of Causes of Unscheduled Maintenance of Hot-Section Components

Combustion Chamber	JP-8	Combustion	8
		Noncombustion	1
		Cracked	1
	JP-8+100	Combustion	5
		Noncombustion	0
		Cracked	0
HPT Shroud Assembly	JP-8	Combustion	4
		Noncombustion	2
		Cracked	0
	JP-8+100	Combustion	2
		Noncombustion	3
		Cracked	0
HPT Nozzle Assembly	JP-8	Combustion	3
		Noncombustion	2
		Cracked	0
	JP-8+100	Combustion	2
		Noncombustion	2
		Cracked	0
	JP-8 (Post)	Combustion	0
		Noncombustion	0
		Cracked	1
LPT1 Nozzle Assembly	JP-8	Combustion	5
		Noncombustion	4
		Cracked	0
	JP-8+100	Combustion	1
		Noncombustion	1
		Cracked	1
LPT2 Nozzle Assembly	JP-8+100	Nozzle Failure	1
LPT Rotor Assembly	JP-8	Noncombustion	2
	JP-8+100	Noncombustion	1
Turbine Frame Assembly	JP-8	Combustion	12
		Noncombustion	1
		Cracked	0
	JP-8+100	Combustion	2
		Noncombustion	4
		Cracked	0
	JP-8 (Post)	Combustion	0
		Noncombustion	0
		Cracked	1
Augmentor Assembly	JP-8	Mechanical	1
		AB/Aug problem	2
	JP-8+100	Fuel leakage & FOD	2
		AB/Aug problem	3
		Cracked	2
		Mechanical	1
Augmentor Exhaust Nozzle	JP-8+100	Noncombustion	1

Table 27 Scaling of Maintenance Costs to Determine Potential Savings

Maintenance Item	Fuel	No. of Actions	Item Repair $	Total Repair $	Operating Hours	$/hr	Scaled Repair Cost	Potential Savings
Comb Chamber Assembly	JP-8	10	41,256	412,560	6,668	61.87		
	JP-8+100	3	41,256	123,768	10,384		642,475	518,707
LPT1 Nozzle Assembly	JP-8	5	56,326	281,630	6,668	42.24		
	JP-8+100	1	56,326	56,326	10,384		438,579	382,253
Turbine Frame Assembly	JP-8	12	24,752	297,024	6,668	44.54		
	JP-8+100	2	24,752	49,504	10,384		462,552	413,048
							Total	$1,314,008

A better model might be based on whether the hot-section components/assemblies are individually lasting longer because a mix of fresh engines and old engines will seriously skew *mean overhaul time* (MOT) for a set of engines. Such data on individual engines were not available. This points out a weakness in the evaluation program since it is being asked whether 400 hours on JP-8+100 can truly show cost effectiveness on engines that already have over 2000 hours operating time, especially if the engines are in good condition and aren't prone to hot-section problems.

The other question asked was whether the use of JP-8+100 had any deleterious effect on maintenance and operations. In a manner similar to Table 26, Table 28 lists the generalized causes for unscheduled replacement of fuel-system components. With few exceptions, the causes were given as "fuel leakage" or "control system component malfunction." It is not known exactly what this latter cause encompasses.

There is nothing in these data to suggest that the use of JP-8+100 had any effect on the maintenance requirements of these items. Only for the case of the augmentor fuel control is the difference between the number of actions due to fuel leakage more than one.

The major maintenance item in Table 28 is the augmentor fuel temperature controller. According to maintenance personnel of the 178th FG, they received a batch of bad controllers; thus, the item is not relevant to possible effects of JP-8+100.

The main engine fuel control was the next most important maintenance item in Table 28. Nine main-engine fuel controls were replaced during the 23-month historical period on JP-8, for an average of 741 hours/replacement, but only five were replaced while flying on JP-8+100, for an average of 2,077 hours per replacement. However, a design defect was found to be causing the problem, and a modification resulted in the reduction of maintenance actions on fuel controls during the JP-8+100 demonstration period. Clearly this reduction in maintenance was not due to the use of JP-8+100.

Aborts

Detailed summaries of the causes for are presented in Tables 21 through 25 for the three analysis periods. During the historical period on JP-8, data on the number and causes of aborts were only available for the eight months immediately preceding the JP-8+100 test period. Figure 32 presents the abort history for the test aircraft for the three periods considered. About one year into the +100 test period, there was a significant increase in the frequency of aborts that continued for the rest of the program, despite the relatively constant number of flight hours per month.

Table 28 Generalized Summary of Causes of Unscheduled Maintenance of Fuel-System Components

Main Fuel Control	JP-8	Leakage	1
		Control system component malfunction	5
		Other	3
	JP-8+100	Leakage	1
		Control system component malfunction	3
		Other	1
Main Fuel Pump	JP-8	Leakage	2
		Control system component malfunction	2
		Other	0
	JP-8+100	Leakage	3
		Control system component malfunction	1
		Other	0
Augmentor Fuel Pump	JP-8	Leakage	5
		Control system component malfunction	1
		Other	1
	JP-8+100	Leakage	4
		Control system component malfunction	2
		Other	1
	JP-8 (Post)	Leakage	2
		Control system component malfunction	0
		Other	0
Augmentor Fuel Control	JP-8	Leakage	1
		Control system component malfunction	2
		Other	1
	JP-8+100	Leakage	3
		Control system component malfunction	1
		Other	1
Augmentor Fuel Temperature Controller	JP-8	Leakage	0
		Control system component malfunction	6
		Other	2
	JP-8+100	Leakage	0
		Control system component malfunction	10
		Other	2
	JP-8 (Post)	Leakage	0
		Control system component malfunction	1
		Other	1
Fuel/Oil Cooler	JP-8+100	Unknown	1

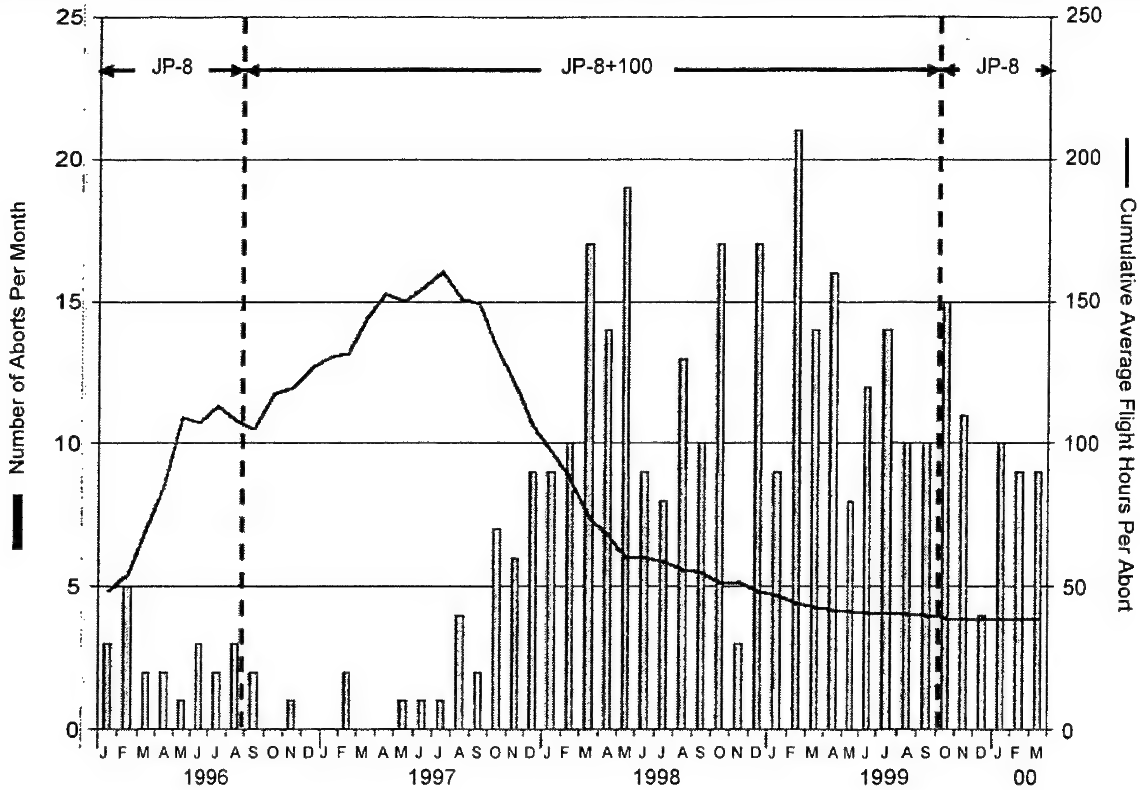


Figure 32 Historical Summary of Monthly Aborts

Superimposed on the abort data is the cumulative average flight hours per abort, confirming that the average number of flight hours per abort began to drop sharply after August 1997 when the 178th began flying on JP-8+100. When asked about the sudden increase in aborts after August 1997, the logistics personnel of the 178th FG expressed surprise since they did not feel that there had been any significant change in the number of aborts. It is possible that adequate records were not being kept prior to August 1997.

For whatever reason, there are insufficient data on aborts prior to the conversion to JP-8+100. Therefore, to draw conclusions about the impact of JP-8+100 on the aborts, one must look at the reasons for the aborts. The detailed reasons for the aborts provided in Tables 21 through 25 are tedious to sort through since most occurred only once or twice over the program period. To facilitate comparison, these causes for aborts have been sorted into the following generalized categories, where EEIC refers to *Electrics, Electronics, Instrumentation, and Controls* and M/H refers to *Mechanical and Hydraulic* systems:

- EEIC (Engine)
- EEIC (Airframe)
- EEIC (Cockpit)
- EEIC (Computer Systems)
- EEIC (Accessories)
- M/H (Engine)
- M/H (Airframe)
- M/H (Cockpit)
- M/H (Accessories)
- Fuel System (Engine)
- Fuel System (Airframe)
- Smoke/Fumes
- Engine Performance and Operation
- Weapons systems
- Foreign Objects
- Bird Strikes
- Auxilliary Power Unit (APU)
- Unknown

Figure 33 presents the distribution of aborts into these categories for the periods before, during, and after the JP-8+100 test period. One abort was attributed to the engine fuel system in the historical period on JP-8. During the JP-8+100 demonstration period, there were 20 aborts attributed to problems in the engine and airframe fuel systems; these amounted to 6% of all aborts during the period. After the 178th FG returned to using JP-8, there were 10 aborts

attributed to components of the fuel systems; these amounted to 17% of the total for that period. In all three periods, the aborts attributed to various aspects of EEIC accounted for about half of the total aborts.
Table 29 lists all of the aborts that were attributed to fuel system components. Some of these are reoccurring problems on the same aircraft, that is, they weren't fixed; for example Entries 6, 7, 8, and 9 were all from the same aircraft and appear to be similar problems. Also, Entries 11 and 12 are for the same aircraft on successive days, as were Entries 22 and 23. These causes generally fall into the categories summarized in Table 30 according to the three periods.

The most significant problems were "fuel tank feed," "fuel flow proportioner (FFP)," and erratic instrument readings. The "erratic instrument readings" appear to be a reoccurring problem on the same aircraft and can be discounted as initially unresolved. Some further detail was available on the resolution of Aborts 15 to 21 of Table 29 that helps to shed some light on the types of problems that occurred; this information, which was not made available on the other entries, is summarized below:

15. foreign object in external shut-off valve
16. replaced external valve
17. replaced pressure switch
18. replaced pressure switch
19. reset sensor
20. fuel leak resealed
21. replaced vent valve

All of the problems listed in Table 30 are isolated with respect to time and aircraft with no indication of common problems. For example, the three fuel-feed problems were entirely different: one from a center-line tank, one from an external tank, and one due to a faulty pressure switch. Based on the information available, it is concluded that despite the statistics, using JP-8+100 did not cause any operational problems.

After the 178th FG returned to using JP-8, the percentage of aborts attributed to fuel-system problems was only a little higher than for the period on JP-8+100 when reoccurring problems on the same aircraft are accounted for. As during the JP-8+100 test period, there does not seem to be any specific problem that occurred due to the change.

3.5.2.3 Summary and Conclusions

JP-8+100 was evaluated for effects on maintenance and reliability of F110-GE-100 engines powering F-16C/D aircraft. This was accomplished by identifying critical components of the fuel system and hot section and monitoring unscheduled maintenance actions for 37 months. All 18 aircraft assigned to the 178th FG were converted to JP-8+100; there were no control aircraft flying only on JP-8. During the test period, some aircraft were temporarily deployed to other air bases and flew on JP-8; those operating hours were not counted in the evaluation. A total of 33 engines were involved in the evaluation due to various engines coming into the shop for maintenance or being returned to depot for overhaul. The operating hours and hence maintenance conditions of the engines were quite varied when they began burning JP-8+100. Some were badly in need of hot-section maintenance; others were fresh from overhaul.

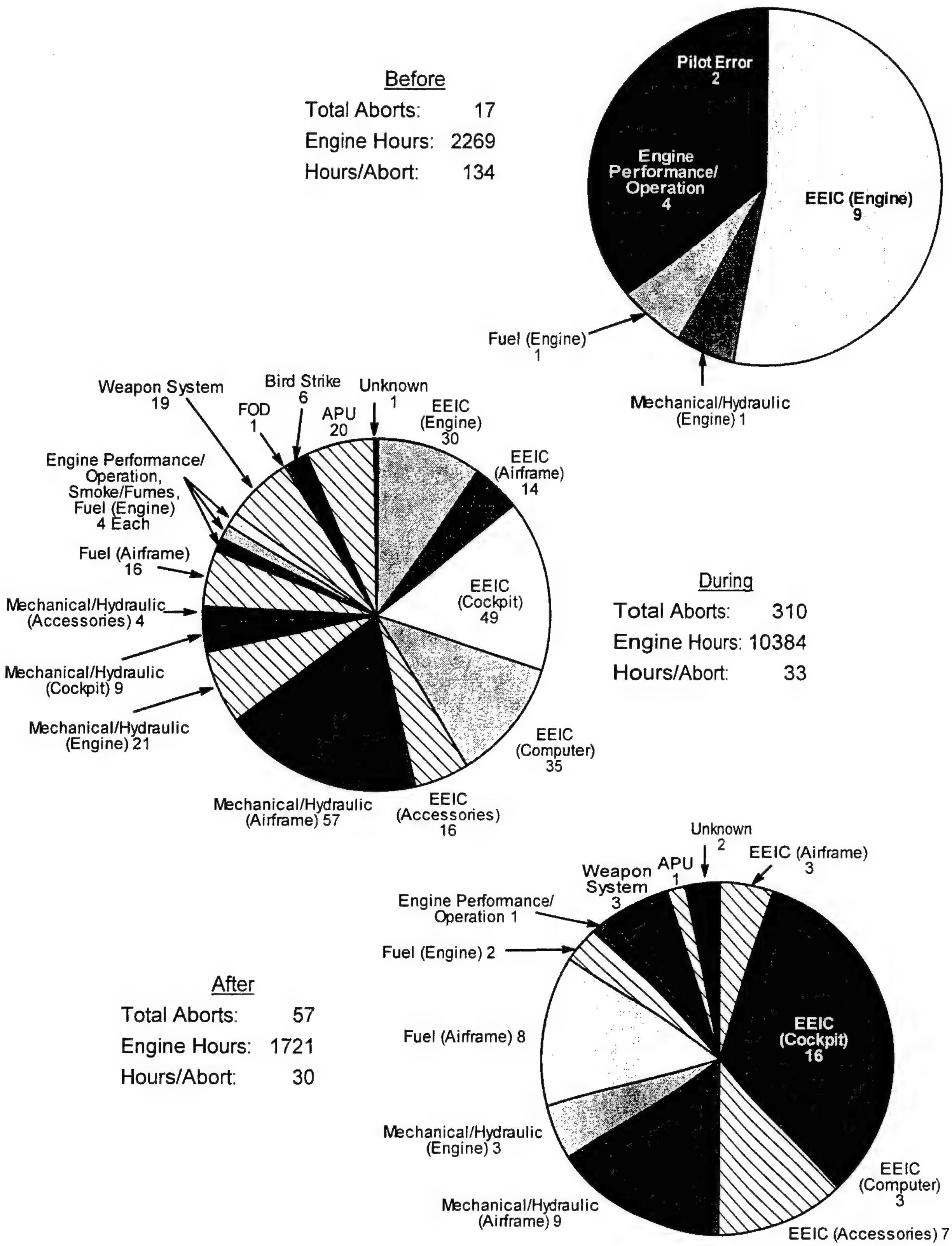


Figure 33 Distribution of Causes of Aborts Before, During, and After JP-8+100 Demo Period

Table 29 Summary of Aborts Attributed to Fuel-System Problems by the Pilots

Period	Date	Pilot Description of Problem	Category
JP-8 Before Test Program	Mar 96	Air Abort, 1st Flight Engine PLF ***(Main Fuel System)***	Engine - other
JP-8+100 Test Program	Dec 97	Air Abort, C/Line Fuel Tank Would Not Feed ***(Fuel Vent/Pressure Installation)***	Airframe – fuel feed
	Mar 98	Ground Abort, Rt. Wing Tank Leaking Fuel From Cap ***Fuel Tank Installation***	Airframe – fuel leak
	Mar	Air Abort, External Tanks Wouldn't Feed ***Fuel Tank Installation***	Airframe – fuel feed
	Apr	Ground Abort, FFP Light Intermittent ***Fuel Feed System***	Airframe – FFP
	May	Ground Abort, Fuel Flow at Idle Showed Between 400-500 pph ***Main Fuel Feed SysestemComponents***	Engine – erratic readings
	May	Air Abort, Fuel Indicator Needle and Totalizer Were Erratic ***Fuel Pump***	Engine – erratic readings
	May	Air Abort, FMS 004 and FDR 044. Needles Went to 400 lb ***Main Fuel Comtrol System***	Engine – erratic readings
	Jul	Ground Abort, FMS 004 MFL - APG Removed ***Main Fuel Control System***	Engine – erratic readings
	Oct	Ground Abort, Rt Fuel Reservoir Was Between 200-250 lb ***Fuel Tank***	Airframe – other
	Dec	Air Abort, Trapped Fuel Warning in Hud. Tank Showed Feeding ***Fuel Tank Installation***	Airframe – other
	Dec	Ground Abort, Excessive Discharge Pressure From Left Underwing Vent ***Fuel Tank Installation***	Airframe – fuel venting
	Dec	Ground Abort, No FFP Light ***Main Fuel Feed System***	Airframe – FFP
	Dec	Ground Abort, Fuel Pump #6 Intermittent FFP Not ***Fuel Tank Installation***	Airframe – FFP
	Jan 99	No Flt, Grnd Abort, During Grnd Chk of EPU ACFT Vented Fuel Out of Left Wing	Airframe – fuel venting
	Jan	Air Abort, External Tanks Feed Intermittently	Airframe – fuel feed
	Feb	No Flt, Grnd Abort, FFP Light Flashing in Idle and Throttle Up Position	Airframe – FFP
	Feb	No Flt, Grnd Abort, #3 Fuel Boost Pump Inop Press to Test	Airframe – fuel feed
	Aug	No Flt, Grnd Abort, Main Fuel Filter Bypass Indicator Popped Aft	Airframe – filter bypass
	Sep	No Flt, Grnd Abort, Fuel Leak Rt Top Wing Around Falcon Up Plate	Airframe – fuel leak
	Sep	Air Abort, SOF Noticed Fuel Venting on Takeoff	Airframe – fuel venting
JP-8 After Test Program	Oct 99	No Flt, Ground Abort Main Fuel Filter Bypass Indicator Extend	Engine – filter bypass
	Oct	No Flt, Ground Abort Main Fuel Filter Bypass Indicator Extend	Engine – filter bypass
	Nov	No Flight, Ground Abort FFP Light Flickers Above Idle	Airframe - FFP
	Nov	No Flt, Ground Abort #3 Boost Pump Inop. Bulb Check Good Eng	Airframe – fuel feed
	Nov	No Flt, Grnd Abort C/L Tank Leaking from Aft Seam	Airframe – fuel leak
	Dec	No Fligt, Ground Abort FFP Light Flickers	Airframe - FFP
	Dec	Air Abort, Centerline Tank Wouldn't Feed	Airframe – fuel feed
	Dec	NO Flight, Ground Abort, Center Line Tank Reads Zero	Airframe - other
	Mar 00	Fuel Indic Prob. Totalizer and Both Fuel Needles Indic. Zero	Airframe - other
	Mar	No Flight Ground Abort FFP Light Flickered at Idle and at	Airframe - FFP

Table 30 Generalized Summary of Causes of Aborts Attributed to the Fuel System

Cause	JP-8	JP-8+100	JP-8(post)
Fuel leakage	0	2	1
Fuel venting	0	3	0
Fuel tank feed	0	4	2
Filter bypass indicated	0	1	2
Fuel flow proportioner problem	0	4	3
Erratic instrument readings	0	4	0
Other	1	2	2

Historical data for the 23 months prior to the test period were collected and used to evaluate the impact of JP-8+100 on the unscheduled maintenance of the F110 engine. Data were also collected on flight aborts and causes, but historical data were only available for the nine months just prior to the test period. The evaluation of the maintenance data included visits to the 178th FG for discussions with the Engine Maintenance Group.

Although there were differences in the abort rates and overall maintenance actions of tracked items before, during, and after the test period, none could be solely attributed to JP-8+100. There was a significant decrease in unscheduled maintenance of the hot section that would have saved about $1.3M if attributed to the use of JP-8+100. However, the maintenance personnel of the 178th FG believe the reduction in maintenance was primarily due to their having recently finished extensive hot-section maintenance on the engines.

Conversely, there was a significant increase in the number of aborts recorded in the data base after the conversion to JP-8+100. It is possible this was due to inadequate record keeping prior to the conversion. In any case, aborts attributed to fuel-system components accounted for only 8% of the total during the evaluation period, some of which were instrumentation problems. Problems that might have been caused by the fuel change, such as leaks and hardware problems, were isolated and sporadic, with no commonality. This lack of commonality continued when the 178th converted back to JP-8, and there were no problems reported when aircraft were deployed and temporarily switch back and forth between JP-8 and JP-8+100.

It is therefore concluded that, for this 37-month demonstration test, JP-8+100 had no verifiable impact on maintenance costs or operations of the F110-GE-100 engines. There were no apparent benefits or detriments.

3.5.2.4 Recommendations

There was nothing in the data or the analyses of this study to suggest any deleterious effects of using JP-8+100 in F110-GE-100 engines and F-16C/D aircraft. Neither were any deleterious effects noted when switching back and forth between JP-8 and JP-8+100. It is therefore recommended that JP-8+100 be approved for unconditional use in this engine and airframe.

3.6 Task 3.5.3: F404, TF34, F110-400, and T700 - Navy Program

The task started with a meeting at the Lynn, Massachusetts, GEAE Riverworks Plant, home of the Navy engine programs. The Navy wanted qualitative and quantitative information on carboning in the fuel systems, controls, and hot flowpaths of their engines. They got a good rundown, but few statistics. The Navy wanted to know what had to happen to get (GEAE) approval for field trials tests that could lead to either limited or unrestricted use of the additive in their engines. The Navy wanted GEAE to develop a proposal architecture they can use to define a program to their management, which their management can then propose to GEAE management at a high enough level to cause flowdown of the Navy desires into all GEAE engine systems groups simultaneously.

- GEAE agreed to review University of Dayton Materials compatibility tests to list out the materials in GEAE fuel systems not yet tested.
- GEAE agreed to do the same for hot-corrosion testing, ongoing at Rolls-Royce, for turbine flowpath materials. A proposal for testing GE materials was made and carried through.

- GEAE agreed to consider doing all materials testing with copper-contaminated fuel — to better characterize Navy shipboard fuel. After careful consideration, the idea was shelved because it was not deemed cost effective.

The University of Dayton Research Institute (UDRI) provided an up-to-date listing of their materials-compatibility test results. A proposal to do hot-corrosion testing was assembled, including rough-order-of-magnitude cost. Information identifying the hot flowpath materials was gathered for the Navy engines and compared to an existing list for Air Force engines to assess commonality. Work on proposal architecture was then started to determine how many Navy engines could be qualified to use the additive by similarity. (Would permit the Navy to begin service evaluation, if they desired.) This comparison indicated that the F110-GE-400, TF34, and J85 can be qualified by similarity. All the materials in the F414 hot flowpath are found in the F110-GE-129 or F110-GE-400; however, as this engine model, and the F404-GE-400 (-402), are considered to be under warranty, an engine test was proposed.

3.6.1 Engine Test Proposal

A tentative plan was submitted to GEAE Lynn Engineering for introducing Navy engines to the +100 additive. The elements of the plan were to run an F404 CIP engine using the additive, to establish capability with the most numerous engine in the Navy inventory, and an engine that has a high pressure ratio and a high-temperature cycle. The main concern of the Navy was to minimize engine testing where possible and to get to service evaluation, in their fleet, as quickly as possible. A secondary concern was engines under warranty versus engines not under warranty. Accordingly, the plan would permit immediate service evaluation to begin on those engine models which have Air Force counterparts already undergoing fuel testing in ANG squadrons. This population would include the F110, TF34, and J85.

The T700 and T64 hot-section bills of materials are the same as the TF34. The plan would permit service evaluation to begin on these two engine models after a fair population of the TF34 engines, being tested, had reached 500 hours of experience with the +100 additive. The current fleet of 16 to 20 engines is at about 250 hours of experience.

The T58 has a cycle and hot-section bill of materials very similar to the J85 engine. There are about 200 J85 engines using the fuel, at Sheppard AFB in Texas, and they have an average of over 600 hours per engine as of this report.

The F414 engine model could be certified with additive at the time it is brought to production status.

Warranted Navy engines are the F404, T700 and T64-419.

The tentative plan submitted to GEAE Lynn Engineering for introducing Navy engines to the +100 additive received comments from GEAE Engineering relative to elastomers in the older controls, silver-plated nuts holding turbine parts together, and near the flowpath. An action plan was put together to capture a J85-5 control and fuel pump from a high-time engine at Sheppard AFB for analysis and inspection and to do the same for a TF34 engine from Barnes.

3.6.2 TF34 Engine Inspection Results

The TF34 from the 104th at Barnes was ESN 205568 with 438 hours running with JP-8+100 fuel and about 100 hours with JP-8, previously. This engine was inducted into the engine house in early April for disassembly and inspection. Funding was provided for shipping the control to Woodward Governor, and the pump to Vickers, for operability checks and teardown inspection and rebuild, as described below.

The control was a Type 3013, Model 8062-353, Report No (s/n-date) 21127-970505. It was subjected to an in-bound operability test. Functionally, it was near or within limits. Woodward noted that it had apparently been disassembled, repaired, and recalibrated at a non-Woodward facility, which may have accounted for some of the out-of-limits noted. Disassembled, the control was clean, and most of the packings and seals were still serviceable, although aged. The technician noted that the control came apart more easily than most, and the level of lubricity between the parts seemed higher. The control was refurbished and returned to Barnes in early September.

The fuel pump (Model PF4-09-6A, P/N 412102, S/N MX321228, Rpt. No. 97-43656-010) was inspected at Vickers. It was shipped new 03/1978. No operational or inspection history was available. In-bound, a functional test was started and halted due to excess leakage. The impeller nut and drive shaft end were worn enough to prevent sealing. Wear was external to the fuel and due to movement of parts during operational life of pump. The nut was replaced with a new part, and all original packings were kept in place. The retest of the pump yielded new part flows. As

tested, the pump flowed 18.08 gpm at 650 psig and 18.4 gpm at 245 psig versus a required flow range of 17.45 gpm to 19.0 gpm. At cranking, 2.28 gpm was measured versus a 2.03-gpm minimum requirement. Disassembled, all the packings were intact, showed no signs of cracking, and appeared to retain the elastic characteristics. One packing is a fluorocarbon compound, and the rest are fluorosilicon. Vickers' opinion was that all the packings were in typical condition and did not appear to have been affected by the environment in which they operated. There was no indication of adverse effect on any of the components in the pump. The worn parts and all packings will be replaced and the pump returned to service.

Planning continued to determine what needs to be done and what parts can be obtained to satisfy the questions with regard to silver-plated fasteners. The problem with the silverplate stems from damage observed on another program: hot-gas corrosive attack on the silverplate that actually damaged the flange though which the fastener was mounted. The part failed locally at that point. Metallurgical inspection of the TF34 parts showed no problems on the silver-coated parts. The following letter report was provided by GEAE Lynn Mature Engine Engineering:

> The following TF34-100A engine (ESN 205568) hardware, that has accumulated 438 hours on JP-8+100, was returned to the General Electric plant at Lynn MA for review and evaluation.
>
> 1 stage 1 nozzle segment
> 5 stage 1 nozzle nut and bolts (silver plated)
> 2 stage 1 blades
> 1 stage 2 blade
> 1 stage 1 shroud
> 1 stage 2 shroud
> 1 stage 2 nozzle
> 1 inter stage seal
> fwd stage 1 cooling plate
> aft stage 2 cooling plate
> 5 nuts from stg. 1 cooling plate
> 5 nuts from stg. 2 cooling plate
> HPT inner casing
> 1 stage 3 nozzle
>
> A visual inspection of all hardware was made at the GE Lynn Thomson Lab. The hardware showed a purple discoloration that is typical of other hardware that has been run with the JP8+100 fuel. The deposits on all the hardware were similar so only the stage one and two turbine blades and the stage one nozzle were analyzed.
>
> All the hardware was received in good condition. The stage 1 and 2 blades had light purple surface deposit visible on the suction side toward the trailing edge. Examination by XRD and XRF showed that the bulk of the thin purple surface deposit on the stage one and two blades to be primarily amorphous phase and phosphorus-rich, with aluminum oxide and aluminum phosphate. The aluminum on the blades is from coatings. A thicker and more deeply purple colored deposit was removed from stage 1 nozzle. Examination of this deposit showed crystalline cobalt phosphate.
>
> The phosphate additive in JP8+100 appears to have caused very slight attack in the substrate in this test. The analysis that the deposit is Cobalt phosphate further indicates reaction with the hardware. Longer time testing of the hardware would be needed to determine if this reaction leads to turbine airfoil life reduction.

This effectively closed out the matter of silver-plate corrosion. No further actions will be considered.

3.6.3 J85 Engine Inspection Results

A J85 engine, ESN 231925, was inducted for tear-down at Laughlin AFB from the training squadrons at Sheppard AFB. Tear-down and inspection of critical fuel system parts was done at the local repair center. Total hours on this particular engine are not known, but the control, SN GAT 7519, has 567.1 hours of +100 experience on it and has been submitted for operability checks and tear-down inspection. The control was torn-down and inspected at the Sabreliner Corporation. Their report stated that they found no unusual wear or visual deformities in the packings and that the interior and the subassemblies were noticeably cleaner than on units normally overhauled. The packings and O-rings were returned to AFRL/PRSF where UDRI tested the materials to confirm the visual findings. These tests assessed deformation, embrittlement, and surface corrosion.

This inspection was the third time a control with more than 400 hours of exposure to the +100 additive has shown no detrimental effect.

A letter to the Navy Fuels and Lubricants Directorate outlined all the GEAE engine experience to date on JP-8+100 fuel. It was recommend that, on the basis of these experiences, similar Navy engine models be essentially qualified to use the additive. It should be noted that the GEAE Lynn facility has a hook-up from their fuel farm that makes it difficult, if not impossible, to run selected engines on just the JP-8+100 fuel, if other engines are running at the same time. Selective Navy engine models would have to go to other sites for service evaluation of the fuel.

GEAE is preparing to take action to approve the BetzDearborn +100 additive. R. Kamin, the Navy Fuels and Lubricants representative, indicated that when that step was taken, the Navy could consider going ahead to start using the additive. It should also be noted that the F110-GE-400 is a Navy engine model, and it had been run on the additive by this time in the program.

3.6.4 Conclusion

This task has been essentially completed. The Navy will qualify engines when and however they want. It should be noted that solving the additive water coalescer disarming problem and developing a drop in water filter separator will go a long way toward Navy acceptance of the additive. The data collected and reported indicate the Navy engines should have no problems operating on JP-8+100.

3.7 Task 3.6: Assess Fuel Heat Sink Capability Using Fuel/Heat Exchanger Tests

The purpose of this task was to design a set of rig hardware that would then be used to investigate the heat-sink utility of JP-8+100 fuel. The hardware would consist of a fuel/air heat exchanger, a "turbine nozzle component," and a rig fuel system for the five-cup sector in the Room 20 Laboratory, Building 18, WPAFB. The test procedure would be to set the fully assembled test rig at some operating condition, bleed some of the rig inlet air ahead of the rig air heaters, duct that air to a separate air heater, and raise the temperature of the bleed air significantly. This very hot air would then be ducted to the fuel/air heater where JP-8+100 would be used to cool it. The cooled air would then be ducted to the turbine nozzle component mounted behind the combustor and used as coolant while the now hot fuel would be ducted to the rig combustor and consumed. The testing would be used to determine fuel cooling capability and air cooling capability for the turbine hardware and to discover and remedy any general or specific system or fluid problems.

An early meeting was held at the Fuels Branch, AFRL, to discuss the design and manufacture of the turbine nozzle component for the five-cup sector test vehicle. The program background, combustor test vehicle, facility, and instrumentation were reviewed. There was then some discussion as to what type of a turbine nozzle design was desired. Consensus was for a "universal" turbine nozzle section with two sets of vanes, one instrumented and one not. The vane sets were to be designed to be locally replaceable and consistent with engine design, as much as possible. The specific aerodynamic design of the vane was not decided, although several candidates (GE90, F110, XTE76, CF6-80) were put into a list. The Fuels Branch also had a goal of determining the effects of the unsteady nature of the combustion process and the turbulence levels of the flow approaching the nozzle vanes.

The general discussions that followed included using a fully aerodynamically designed vane, how to return the turbine nozzle exiting gas stream to axial direction as quickly and simply as possible, air-cooling the support structure around the cascade, water-cooling the end walls and end-wall vanes, using quench water for the downstream rig structure and then putting it into the exhaust flowpath, variable interface with the combustor sector, aspects of the required heat transfer and stress torque analyses of the test section, and rig operating capability.

The action items that resulted from this meeting were to decide on a cycle design point and a comparable vane aerofoil shape and start the sector design.

Initially, the component rig design engineer concentrated on defining the rig support structure and methods for delivering services to the test section. For this work, an F110 turbine airfoil shape was used as a strawman in the flowpath. Work was started immediately on an instrument section that would sit in the rig when the nozzle section was not there, routing of combustor fuel and cooling water lines, a services case, and an extension piece which would mount at the turbine nozzle exit flange and connect to the exhaust plenum.

A quotation for the heat exchanger was obtained. The casing design permits replacement of the coils to facilitate repair of damage and upgrades as more capability is required. The decision was made to procure a unit with capability of producing 1000°F fuel temperature and handling 1200°F air temperature. The interiors of the coils were to be coke-barrier coated. The heat exchanger design was from Graham Manufacturing Company, Batavia, NY: a Model 303C3C-28L, Heliflow, weight 4,000 lbm, and approximately five feet on a side.

Design work was completed on the turbine airfoil section. The airfoils were based on the XTE76 design, and heat transfer analysis to define the details of the impingement shields inside the airfoils was completed. The test section has seven airfoils, five of which are air cooled, and the end-wall airfoils are water-cooled. This provides four air passages between airfoils unaffected by cold surfaces. Two manufacturing methods were examined. In one, the vanes would be cast. In the other, the vanes would be wire-cut and brazed together.

3.7.1 Test Facilities Engineering Design Report (Deleted – See Full Report)

3.7.1.1 Scope (Deleted – See Full Report)

3.7.1.2 Air-Cooled-Vane Heat Transfer Study Results (Deleted – See Full Report)

3.7.1.3 Work Required to Complete the Design and Issue the Drawings (Deleted – See Full Report)

3.7.2 Conclusions, Assess Heat Sink Capability Task (Deleted – See Full Report)

3.7.3 Hot-Corrosion/Erosion Materials Testing

A hot-corrosion component test was added to the program. Material selected from the engine hot-section material list was assembled, and testing took place in Cell 11, Building 703, Evendale, run by the GEAE Materials Lab. The test apparatus, called BECON rigs, consist of a small cannular combustor with an approximate four-inch-diameter exhaust gas stream. Set at right angles to this exhaust stream is a rotating and translating circular platform or disk, called a carrousel. Near the edge of the disk surface are 11 holes into each of which can be inserted a material pin, a quarter inch in diameter and about four inches long. The disk spins on a centerline axis and, in translation, can insert the pins into the combustor gas stream or remove them. Generally, the top three inches of the pin are exposed to the hot gas stream. The gas stream has an inherent temperature profile that is measured so that the gas stream temperature distribution on the pin is known. The gas stream peak average temperature was set at either of two levels, depending on which set of materials was being tested. The test runs for 400 hours, total, unless the pins do not last that long.

The pins are cycled into and out of the gas stream in a 15-minute cycle. Four minutes are spent at about 500°C (932°F), then the temperature is increased to 1135°C (1895°F) for ten minutes, then the samples are moved out of the gas steam for a minute to cool, and the cycle is then reinitiated. A full test is 1600 cycles. Two pins of each material were placed on the carrousel platform. There was also one bare metal Hast X pin that acted as a tare.

The fuel used throughout was JP-8. Fuel was fed to the cell from a 1000-gallon, trailer-mounted tank. The additives used were injected into the fuel as it was pumped into the trailer-mounted tank from the storage tank.

The materials selected for the high-temperature testing (Group 1) were HS188, Inco 718, Hast X, Advanced Material 1 and Advanced Material 2. The Advanced Material 1 was Codep coated; the Hast X had 0.01-in, air-plasma sprayed (APS) TBC. The materials selected for the lower temperature testing (Group 2) were Inconel 718, Hast X with TBC, L605, Waspaloy and Incoloy 909. A summary of the testing is shown in Table 31.

Neat JP-8 was run first as a baseline. The Hast X samples were replaced with bare Hast X pins when the TBC bond coats failed and local spalling of the TBC took place near the 200-hour point of this test. The Inco samples were

replaced with Hast X dummy pins at about 300 hours due to severe erosion of the material in a gas stream that was several hundred degrees too hot for this material. (The Inco was just melting away.) The HS188 samples had some material loss, as did Advanced Material 2. The coated Advanced Material 1 appeared to come away with little damage. Some pitting occured on the Advanced Material 2 pins.

Table 31 Hot Corrosion Tests Completed

Fuel	Additive	Test Date	Gas Temperature	Materials	Comments
1. JP-8	None	November 1996	1135°C	Group 1	Baseline
2. JP-8+100	A-1	January 1997	1135°C	Group 1	Tare for Others
3. JP-8+100	B-1	March1997	1135°C	Group 1	First of three
4. JP-8+100	C-1	April - May 1997	1135°C	Group 1	Not selected
5. JP-8	None	June - July 1997	954.5°C	Group 2	Baseline
6. JP-8+100	A-1	August 1997	945.5°C	Group 2	Tare for Others
7. JP-8+100	B-2	Oct - Nov 1997	945.5°C	Group 2	High Corrosion
8. JP-8+100	D-1	March - April 1998	1135°C	Group 1	Low Corrosion
9. JP-8+100	B-3	July - August 1998	945.5°C	Group 2	Better than R. 7
Group 1 Materials: Inco 718, Hast X with TBC, HS188, Advanced Material 1 with Codep, Advanced Material 2.					
Group 2 Materials: Inco 718, Hast X with TBC, L605, Waspaloy, Incoloy 909 (in lieu of 907)					
Uncoated Hast X pins were used as a control on the carousel in each test.					

The second test of the series was initiated in December. This test used the same material samples as the baseline, but the fuel was JP-8, with A-1 additive at normal (256 ppm) concentrations. See figure 43 in Appendix A

The third test was with the first of three B Corporation additives, B-1, and added to the JP-8 in a concentration of 180 mg/L (ppm).

The properties of both additives, A-1 and B-1, affected the materials in similar manner. The coated metals were not affected. The uncoated Advanced Material 2 had very little additional weight loss when the additives were in the fuel. The uncoated HS188 and Hast X suffered about 20% increase in weight loss with the additives, but erosion of the Inco 718 was actually slowed (about 3%) by the presence of the additives. See Figure 44 in Appendix A.

The fourth test was done with C-1, with a dosage concentration of 1100 mg/L (ppm). See Figure 45 in Appendix A.

The fifth test was a new baseline at a lower peak temperature, 954.5°C (1752°F) and the Group 2 materials. See Figure 46 in Appendix A.

The sixth test was done with the A-1 additive and Group 2 materials. Test 2 and 6 results are compared in Figure 47 in Appendix A. Test 5 and 6 results are compared in Figure 49 in Appendix A.

The seventh test was done at the lower temperature condition using the second B additive, B-2, using a concentration of 200 mg/L (ppm). Material loss rates were increased with this additive. See Figure 48 in Appendix A.

The eighth test was with additive D-1. Concentration level was set at 458 mg/L (ppm). This additive was tested at the higher gas temperature and with the Group 1 materials. In general, pin material loss was less than that with the A-1 additive. See Figure 50 in Appendix A.

The ninth and last test was done at the lower gas temperature, Group 2 materials, and reformulated B-3, with a concentration of 250 mg/L (ppm). See Figure 51 and Figure 52 in Appendix A.

3.7.4 Task 3.7: Thermal Stability Evaluation

3.7.4.1 Investigation at Southwest Research Institute

The SwRI investigation of fuel thermal stability was documented in "JP-8+100 Atomizer Fouling Evaluation Final Report" (SwRI Project 03-1037) prepared for GEAE by Clifford A. Moses and dated October 2000. That report is replicated on the following pages. The report was reviewed and approved by GEAE while in preparation. It has been recomposed to fit the style, format, pagination, and numbering sequences of this report. The report is otherwise complete, as stipulated by SwRI.

Introduction

There is concern that military aircraft refueled with civilian jet fuel may experience premature fuel fouling problems due to insufficient fuel thermal stability. Aircraft of the U.S. Air Force on occasion are refueled at commercial airports with fuel meeting the ASTM D 1655 fuel specification for Jet A, but not necessarily meeting the MIL-T-83133D fuel specification for JP-8. Specifically, there is a two-tiered temperature provision for thermal stability in ASTM D 1655 that allows for a Jet A fuel that does not pass the JFTOT test at an operating temperature of 260°C (500°F) to be retested at 245°C (473°F); the fuel can be approved for use as Jet A if the fuel passes the test at the lower temperature, providing both results are reported. MIL-T-83133D requires that all fuels pass the JFTOT at 260°C. The significance of this difference is that a fuel which passes the JFTOT at 260°C will have a higher thermal stability than a fuel which fails at 260°C. Fuel used in military engines has less margin available by the time it reaches the engine due to its use as a cooling medium for other systems on the aircraft.

It is not currently possible to conduct any bench-scale deposition tests which could be used to predict the effect of such a change in this measure of fuel thermal stability. Neither is it possible to model the effect. The problem is complicated because the JFTOT test is a pass-fail test based on a deposit color; it is not a quantitative test of fuel thermal stability. Therefore, an experimental project based on the fouling rates of fuel nozzles was used to evaluate the following:

- the effect of a 245°C JFTOT on the fouling rate of fuel nozzles
- the effect of BetzDearborn SPEC AID 8Q462, the additive approved for JP-8+100 on the fouling rates of a 245°C Jet A fuel

Objectives and Scope

The overall objective of this project was to evaluate the effectiveness of JP-8+100 on both operational problems and certain design issues of fuel nozzles. The specific objectives addressed were:

- What is the potential impact of using a jet fuel with a JFTOT rating of 245C?
- Can BetzDearborn SPEC AID 8Q462 be used to improve a Jet A fuel that passes JFTOT at 245°C but not at 260°C?
- If a red-dye contamination reduces fuel thermal stability, can BetzDearborn SPEC AID 8Q462 be used to restore fuel quality?
- Will JP-8+100 clean up a used fuel nozzle containing some deposits?
- How much will the use of BetzDearborn SPEC AID 8Q462 allow the fuel temperature to be increased without exceeding current fouling rates?
- How much will the use of BetzDearborn SPEC AID 8Q462 allow the fuel-wetted wall temperatures to be increased without exceeding current fouling rates?
- Will BetzDearborn SPEC AID 8Q462 have any effect on fuel pyrolysis rates in fuel-wetted tertiary cavities in fuel nozzles that have this design feature?

Approach

Three different experiments were used to address the questions identified above:

1. Fuel nozzle fouling experiments were conducted to address the first five questions on the effect of BetzDearborn SPEC AID 8Q462 on fuel thermal stability and the equivalence of fuel temperature.

2. A special deposition rig that simulates the geometry of fuel flow passages in the nozzle tip was used to address the sixth question on wetted wall temperatures.

3. Another special experiment was used to simulate the thermal environment of a tertiary cavity to address the last question on pyrolysis rates.

These experiments and the test fuels are described separately in the remainder of this section.

Nozzle-Fouling Experiments

The nozzle-fouling experiments were conducted using fuel nozzles from the F110-GE-100 engine. The test pieces were placed in a heated fluidized bed to simulate the thermal environment of the actual engine installation. This is illustrated in Figure 55 while Figure 56 shows the entire flow system. The fuel was not recirculated and was not reused.

Three thermocouples were attached to each test nozzle. One was placed on the tip as the metric for the test condition, and the other two were placed on the stem as references. The location of the thermocouple on the tip was determined by General Electric and is shown in Figure **57**. In conducting a test, the temperature of the fluidized bed was adjusted to bring the temperature of this point to 260°C (500°F) as specified by General Electric as representative of the installed condition.

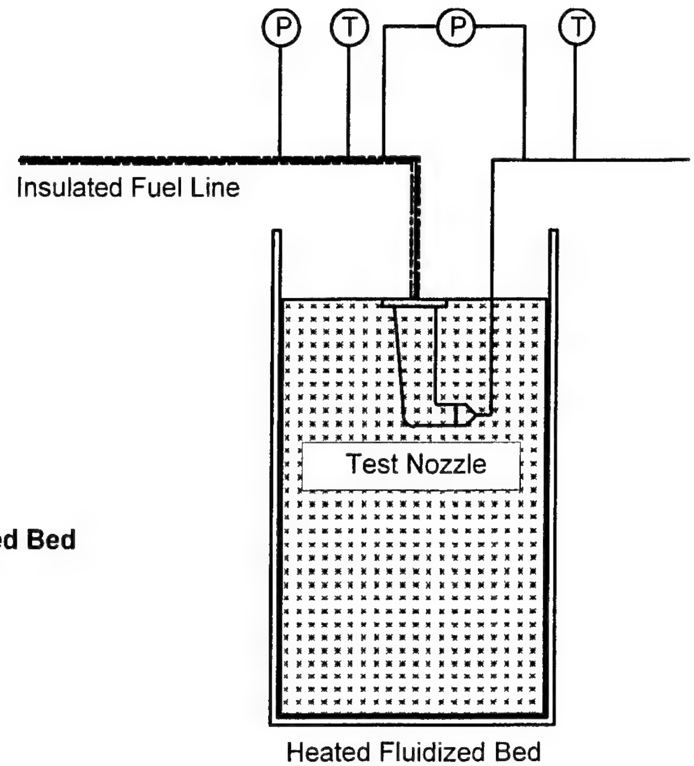


Figure 55 Heated Fluidized Bed

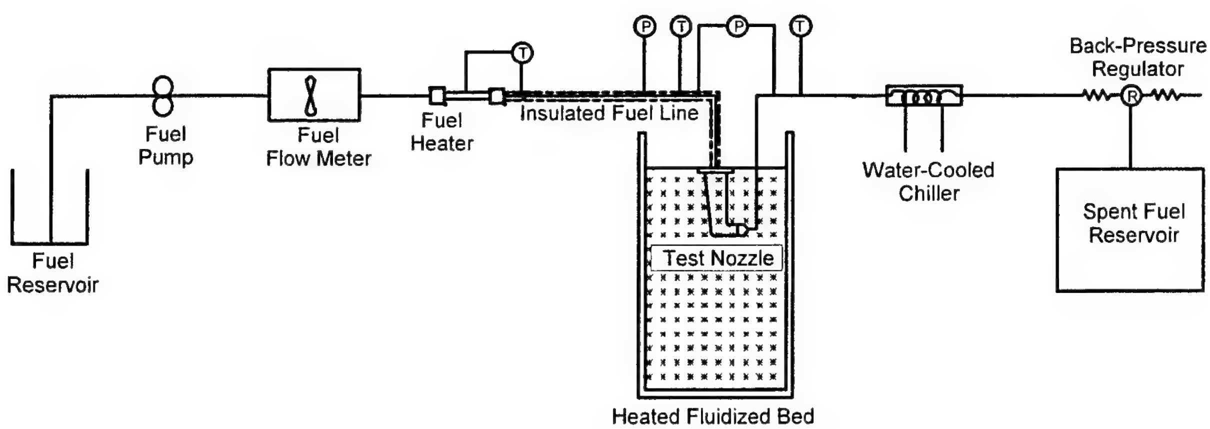


Figure 56 Flow Schematic of Nozzle Fouling Experiments

The test conditions of fuel flow rate and nozzle skin temperature were chosen to represent the beginning of idle-descent. This is the point in a flight where the pilot throttles back to reduce speed from a sustained cruise condition. It is the condition of highest temperatures in the tip of the fuel nozzle because the combustor inlet-air temperatures and metal temperatures are still very hot, but the fuel flow, which is the heat sink for the nozzle, has just been greatly reduced, so there is significant fuel heating. Thus, the fuel deposition rates are highest at this instant. For these tests the nozzle tip temperature was 260°C (500°F).

In order to accelerate the fouling, the fuel inlet temperature was increased to higher than normal. It was desired to have test times on the order of 25 hours to allow for reasonable test times without testing at temperatures where the kinetics of deposition may change. Typical fuel temperatures were in the range of 170° to 210°C (340° to 410°F), about 10° to 50°C (15° to 85°F) higher than experienced in actual flight.

The fuel was heated by flowing it through a narrow annulus created by a 1.6-cm (0.625-inch) diameter electric cartridge heater inserted into a length of 1.9-cm (0.75-inch) diameter tubing; the annulus height was 0.13 mm (0.005 inches), and the heated length was 81 cm (32 inches). This heater design was to minimize the skin temperature of the heater so as not to overheat the fuel; typical temperature difference between the heater wall and the fuel was about 10°C (18°F).

The fuel flow rate and pressure drop across the test nozzle were monitored continuously so that the instantaneous flow number, *FN*, of the nozzle could be determined. The rate of degradation of flow number was the metric used for quantifying nozzle fouling:

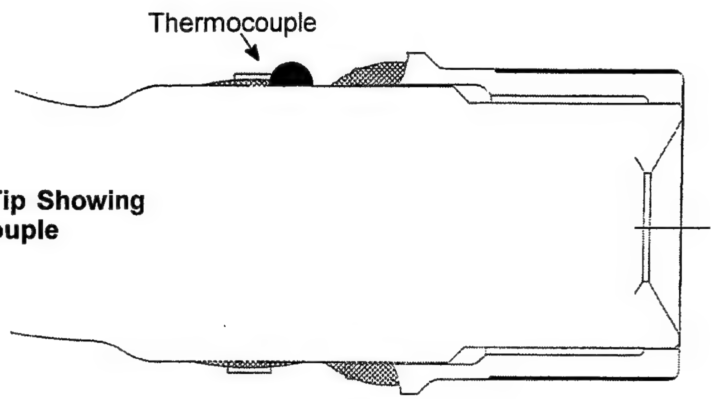


Figure 57 Outline of F110 Fuel Nozzle Tip Showing Location of Control Thermocouple

Fouling Rate,

$$FR = \frac{d(FN)}{dt}$$

where

$$FN = \frac{mf}{\sqrt{\Delta P}}$$

and mf = fuel flow rate, lbm/hr.

Figure 58 presents a typical temperature/time history for the fluidized bed, the tip of the nozzle, and the fuel at the nozzle inlet for one experiment to illustrate the stability of the test conditions over many hours.

Also shown in Figure 58 is the corresponding time history of the flow number, *FN*, of the test nozzle. The relatively linear decrease with time is quite typical. As the fuel temperature is increased, the slope of *FN*, i.e., the fouling rate, *FR*, was found to increase exponentially with fuel temperature. Thus, by testing each fuel at several fuel temperatures, Arrhenius-type plots of FR versus $1/T_{fuel}$ could be generated to show the constancy of the kinetic mechanism and to allow the extrapolation of fouling rates back to more typical operating temperatures. This will be shown in the discussion of results.

Wetted Wall-Temperature Experiments

It is not practical to conduct parametric studies of wetted wall temperature using actual fuel nozzles because of the difficulty in instrumenting the flow passages for wall temperature. Single-tube heat exchangers, STHX, have been used extensively to study fuel deposition rates under conditions of varying wall temperature by many research groups in this field, such as Shell, Exxon, UTRC, WPAFB, and SwRI. Two types of STHX are normally used: isothermal systems, which provide a constant wall temperature after an entrance length of temperature recovery, and those with constant heat flux, which have a temperature gradient along the wall. Both types are felt to have

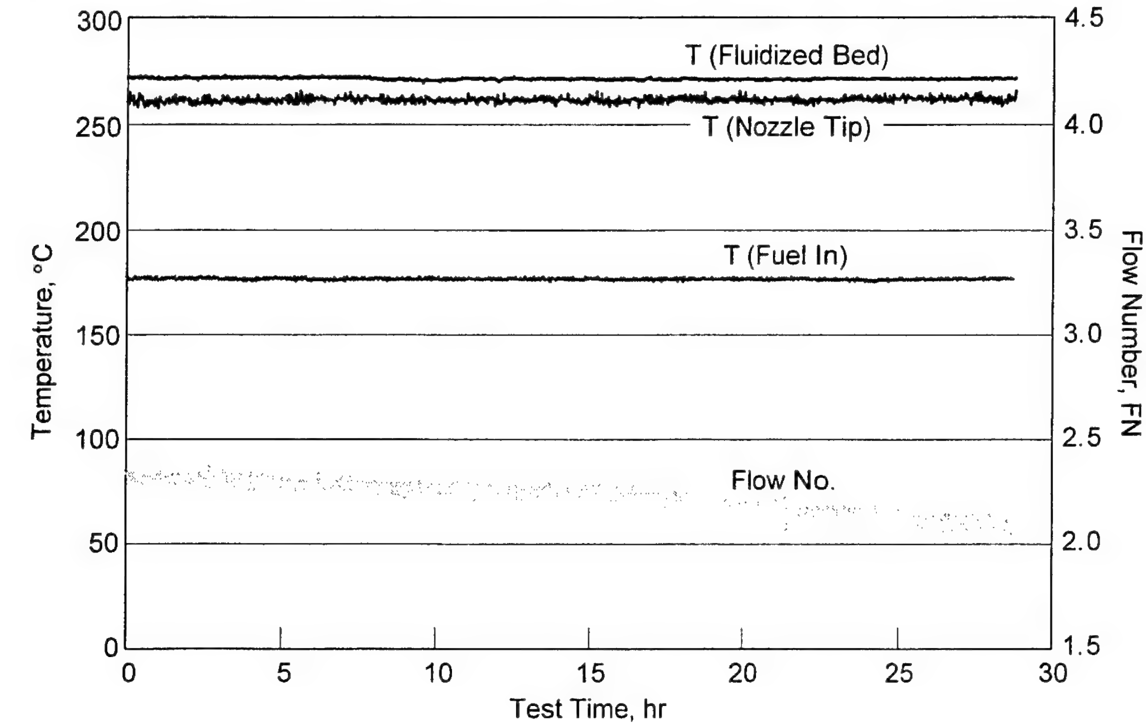


Figure 58 Typical Time History of Test Conditions

deficiencies when used to address the question of equivalent wall temperatures for deposition rate. When using STHX with constant heat flux, the deposition at any point along the wall is not uniquely dependent upon the wall temperature at that point; it is also affected by the thermal history of the fuel upstream of that point such as temperature gradient and oxygen consumption. With isothermal rigs, such as the Air Force Phoenix rig, which have heated sections the order of 50 cm (6 ft) long, the entrance length can be several centimeters, depending upon the flow rate; this is much longer than the characteristic length of a flow passage in the tip of a fuel nozzle.

It was felt that a better choice would be to have a very short isothermal test section that simulated the geometry of a flow passage in the tip of a fuel nozzle and suddenly exposed the flowing test fuel to an increase in wall temperature without any appreciable thermal history. The difficulty in designing such a rig is to provide a high heat flux to minimize the entrance recovery length.

Such a deposition test rig was developed at SwRI in a research program for NASA Glenn Research Center (then NASA Lewis Research Center) to study the deposition problem in simple, pressure-jet fuel injectors immersed in a hot air steam such as might be found in a premixed, prevaporized (PMPV) low-NOx combustor.

This rig was named the SHiQ (Short-tube, High Heat Flux). The basic concept is depicted in Figure 59. The fuel flows through a length of 1.6-mm (0.062-inch) diameter tubing with an inside diameter of 0.56 mm (0.022 inch). The heated section has a length of 6.4 mm (0.25 inches). The heat flux is provided by a band heater wrapped around a 5.1-cm (2-inch) diameter copper cylinder clamped to the test section. The high heat flux rates are obtained by insulating the copper cylinder and forcing all the heat to flow into the heated test section. This unique design allows very high heat flux rates, of the order of 400 W/cm^2 (2500 W/in^2)or more.

Thermocouples measure the outside wall temperature of the tube in the heated section at three evenly spaced axial locations. The wall temperature of the tube is uniform, typically varying only a couple degrees along the length, and can be controlled to any desired temperature even with turbulent flow without exposing the fuel to high-temperature surfaces prior to the test surface. Experiments have been conducted with the SHiQ at wall temperatures as high as 450°C (850°F) with flows of 66 kg/hr (30 lbm/hr) and Re = 15,000. The fuel can be heated to any desired inlet temperature.

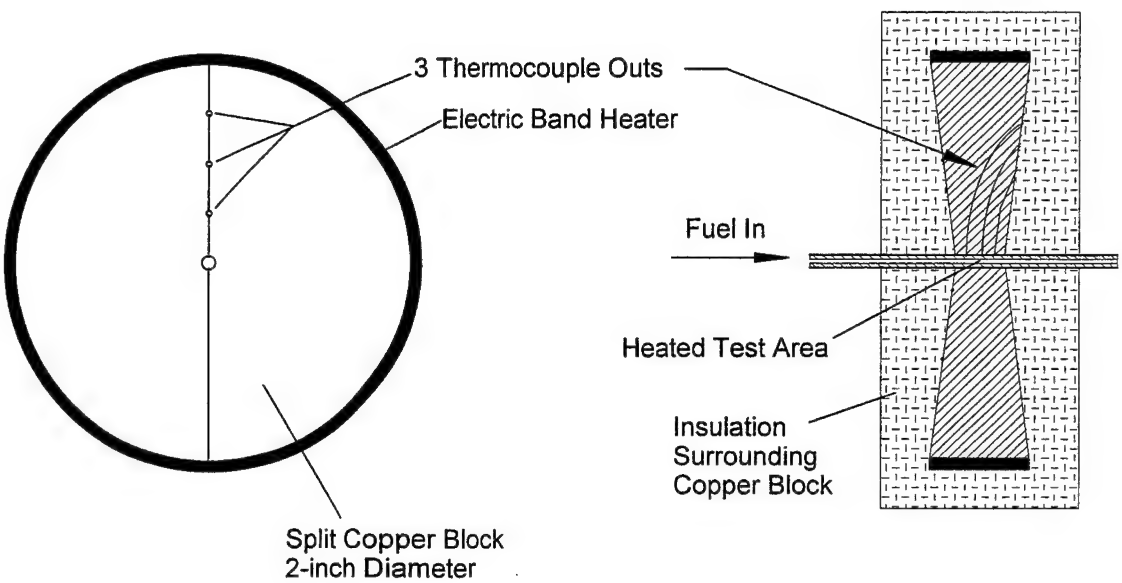


Figure 59 SHiQ Deposition Test Rig

In order to reduce test time and fuel usage, the flow rate for these experiments was 10 ml/min, resulting in an inlet Reynolds number on the order of 100. The test duration was 5 hours. At the end of the test, the heated test section is then cut out and the deposit mass measured by a standard carbon burn-off technique so that deposition rates can be easily determined. At higher flow rates, the test times must be longer to gather sufficient deposit for measurement.

Tertiary-Cavity Pyrolysis Experiments

Tertiary cavities are used on some fuel nozzle designs as a method of heat shielding for the fuel lines traveling down the stem of the nozzle. Tertiary cavities can be dry or wet; in the latter case, fuel leaks into the cavity around O-rings that allow for thermal expansion. The thermal environment is such that the outside wall of the cavity is exposed to compressor discharge air temperature, which could be as high as 593°C (1100°F), while the inside wall is at the fuel temperature, which is more like 150°C (300°F).

A test rig was designed to simulate this thermal environment. The "cavity" was an 20.3-cm (8-inch) length of 1.9-cm (0.75-inch) diameter stainless steel tubing capped at both ends. To simulate the fuel tube inside the tertiary

cavity, a 0.32-cm (0.125-inch) diameter tubing ran axially through the cavity; water flowing through this tube provided the heat sink inside the cavity. The cavity was placed horizontally in a clam-shell radiant oven. The test piece is illustrated in Figure 60. The outside skin temperature was held at a constant temperature of 593°C (1100°F) to simulate an extreme flight condition. The cooling tube inside the cavity was maintained at 93°C (200°F); admittedly this is much cooler than a typical fuel temperature, but a practical maximum when using a simple water coolant and the difference was not considered significant for this test.

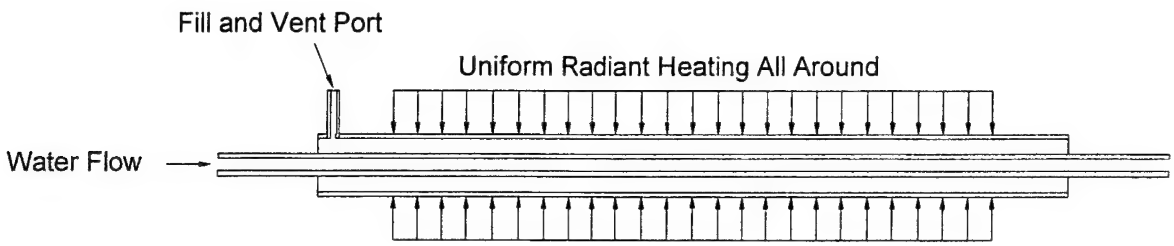


Figure 60 Schematic of Pyrolysis Cavity

At the end of a test, the outer tube forming the cavity wall was split lengthwise. To determine the deposition rate, small sections were cut out of both halves, near the center and at the end of each piece; these were subject to standard carbon-burnoff techniques to determine the mass of carbon on each.

Test Fuels

SwRI was originally provided 2000 gallons each of three JP-8 fuels from WPAFB. These fuels were selected because they had significantly different JFTOT breakpoint temperatures. However, when the breakpoint temperatures were determined after being received at SwRI, there was not much difference. Later in the program, a fourth fuel was shipped from WPAFB which did have a very high breakpoint temperature. Other test fuels were developed from these base fuels by blends of diesel fuel, red dye, and A-1, the thermal stability additive approved for JP-8+100. Table 32 lists all the fuels and their JFTOT breakpoint temperatures as determined by SwRI.

Results and Discussion

Nozzle Fouling Tests

Fuel Nozzle Fouling Tests - Figure **61** illustrates the fouling data taken in this program. Shown are the data sets for the same fuel at three fuel inlet temperatures, 177°, 188°, and 199°C (350°, 370°, and 390°F). The slopes of these curves were then plotted against the inverse of the fuel inlet temperature, in Kelvin, to get an Arrhenius plot such shown in Figure 62 for these same tests. This indicates that the fouling of the fuel nozzles under this methodology at constant flow rate is controlled by kinetics of deposition and that increasing the fuel temperature to reduce testing time did not change the kinetic mechanism.

Figure 63 compares the fouling rates for all of the fuels tested in this project as listed in Table 32. This represents the first time that a number of fuels of different breakpoint and different types of contamination and/or additives have been evaluated in this manner. In general, it seems apparent that these data sets form a family of curves with very similar temperature dependence. This suggests that, for these fuels, the global kinetics controlling deposition and nozzle fouling are essentially the same regardless of the specific factors affecting fuel thermal stability.

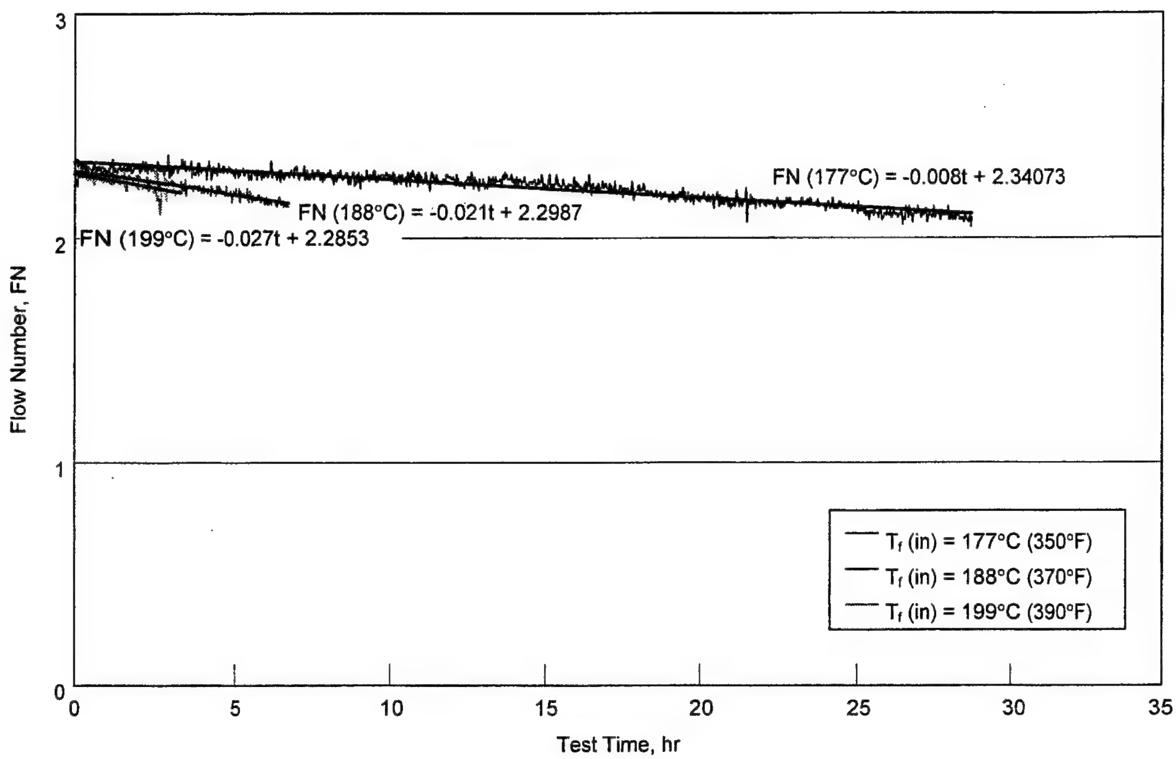


Figure 61 Typical Test Data Showing Effect of Fuel Temperature on Fouling Rate

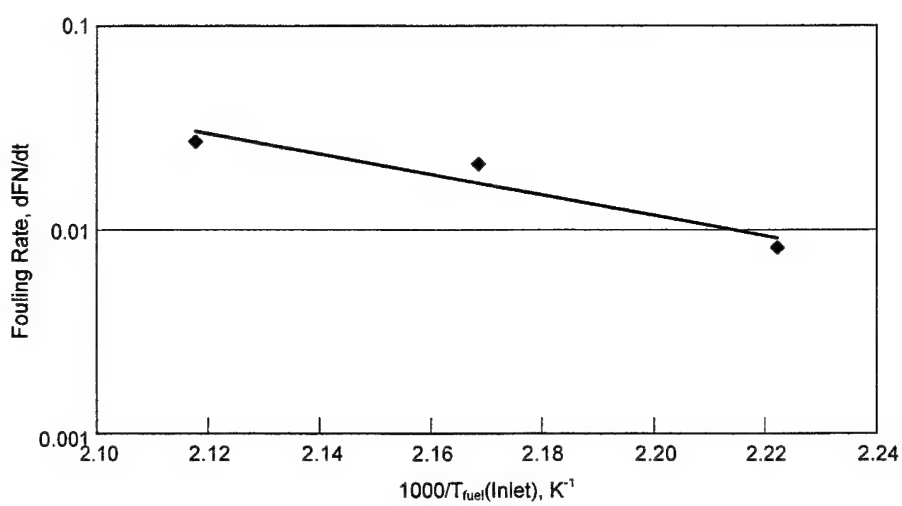


Figure 62 Arrhenius Plot of Nozzle Fouling Rates

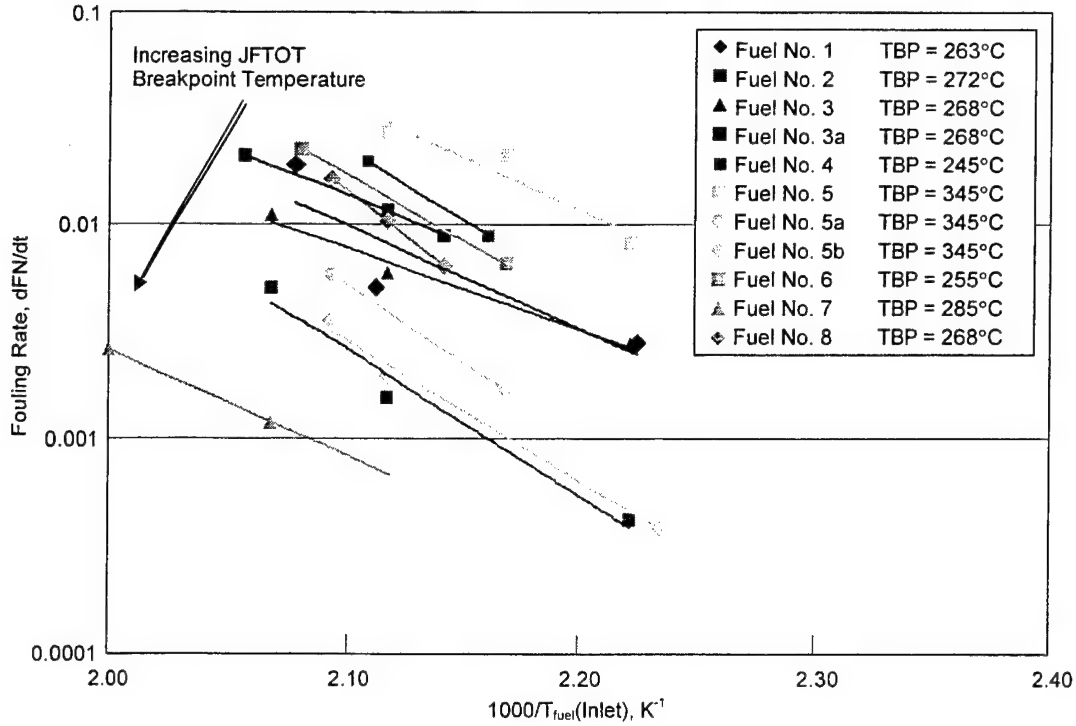


Figure 63 Project Summary of Nozzle Fouling Rates

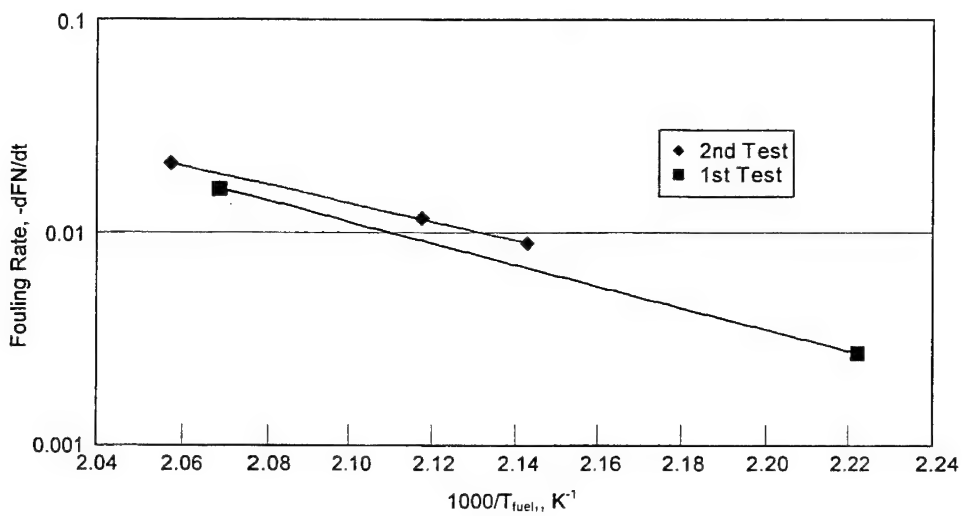


Figure 64 Comparison of Two Test Sequences on the Same Fuel to Demonstrate Repeatability

A formal determination of repeatability has not been conducted for this type of test methodology. However, during the course of the project, one of the test fuels was tested twice over a range of fuel temperatures and the results serve as a good indication of the repeatability. Figure **64** shows the fouling rates for test Fuel No. 2, AL-25017, for two test sequences conducted over a year apart. The agreement of the results is considered to be very good.

Table 32 Test Fuel Summary

Fuel No.			Description	JFTOT Breakpoint
Test	SwRI	WPAFB		
1	AL-25018	POSF-3084	JP-8	263°C (505°F)
2	AL-25016	POSF-2926	JP-8	272°C (520°F)
3	AL-25017	Blend of POSF-3114 and POSF-3084	JP-8	268 (515°F)
4	AL-25679		Fuel No. 1 + 0.5% HSDRF*	245°C (473°F)
5	AL-25832	POSF-3497	JP-8	345°C (653°F)
6	AL-26204		Fuel No. 3 + 1.5% HSDRF*	255°C (491°F)
7			Fuel No. 3 + 1.5% HSDRF* + 8Q462	285°C (545°F)
8			Fuel No. 3 + 0.55 mg/L red dye	268°C (515°F)
9			Fuel No. 6 + 0.55 mg/L red dye	345°C (653°F)
* HSDRF is the Cat-1H high-sulfur diesel reference fuel; it has a breakpoint of about 220°C (428°F).				

Referring back to Figure 63, with the exception of Fuel No. 5, which appears three times in Figure 63, the data sets seem to be fairly well ordered according to breakpoint temperature. Fuel No. 5 was shipped to SwRI by WPAFB after it was found during initial nozzle fouling tests that there was not sufficient difference in the breakpoint temperatures of the original three test fuels to demonstrate a definitive sensitivity of fouling rate to breakpoint temperature. Fuel No. 5 was known to have a very high breakpoint temperature.

Fuel No. 5 was shipped in drums to SwRI, and during the first set of tests the fuels were pumped from the shipping drums. The resulting fouling rates from this initial set of tests were much higher than for any of the other fuels, including Fuels No. 4 and 6, which were contaminated with diesel fuel.

JFTOT tests were conducted on a fuel sample from the drum of fuel being used in these initial tests and was found to immediately fail on pressure drop. Subsequent investigation showed that the filter support had been softened/dissolved by the fuel, probably by an excess of FSII, causing a blockage in the filter. Subsequent investigation of the drum showed that free water was present along with some contamination. This fuel was then decanted out of the shipping drums and retested. The fouling rates were then found to be an order of magnitude less, shown in Figure 63 as Fuel No. 5a. Later, this same fuel, but from other drums, was tested again; the result was an even lower set of fouling rates shown in Figure 63 as Fuel No. 5b. This seemed to confirm the suspicion of contamination, but the question was never resolved. It is interesting that all three sets of data for Fuel No. 5 have about the same slope in Figure 63.

Effect of SPEC AID 8Q462 on an Off-Spec Fuel - One of the major ways that a fuel can go off-spec on thermal stability is due to contamination by a diesel fuel or home heating oil during storage or transportation. Two of the JP-8 test fuels were deliberately contaminated with Cat-1H diesel reference fuel to lower the breakpoint temperature

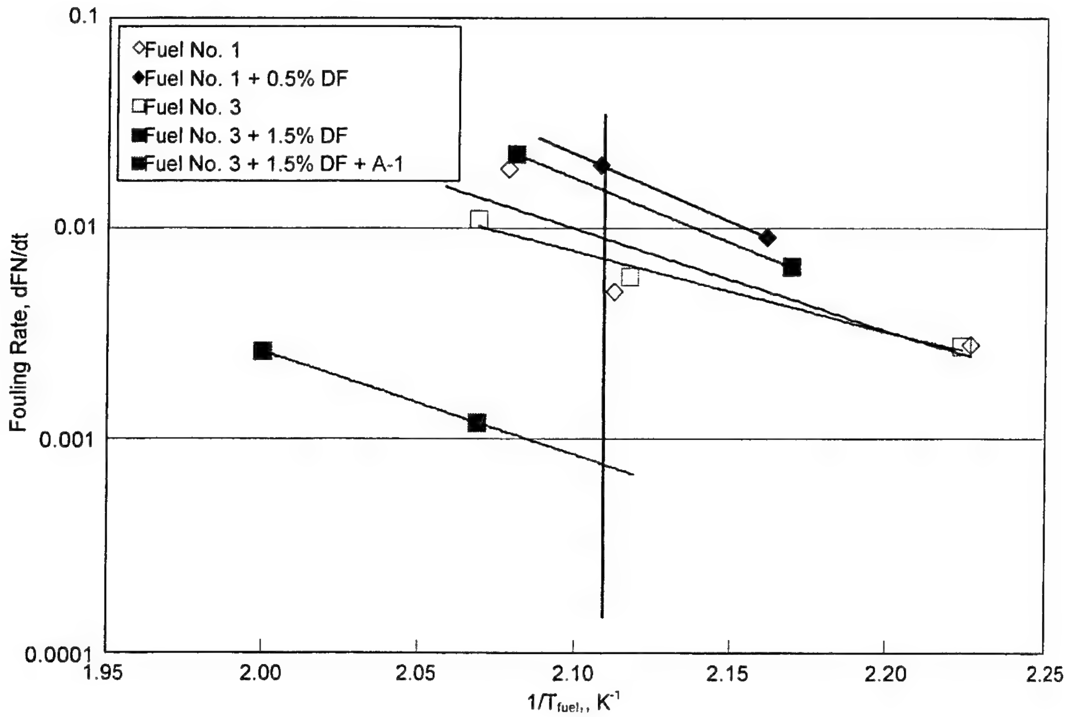


Figure 65 Effect of Diesel Fuel Contamination on Fouling Rate and Use of Thermal Stability Additive to Recover Fuel Quality

such that they failed the JFTOT at 260°C but passed at 245°. Figure **65** compares the fouling rates of the contaminated fuels with the uncontaminated fuels. In both cases the effect of the contamination was to double the fouling rate.

SPEC AID 8Q462 was then added to one of the contaminated fuels at 256 mg/L to evaluate the effect of this additive on a contaminated fuel. The effect of the additive was to reduce the fouling rate by almost 95%.

Table 33 summarizes the pertinent data on contamination level and the effect on breakpoint temperature and fouling rate at a fuel temperature of 200°C (392°F).

Table 33 Effect of Diesel Fuel Contamination on Thermal Stability and Fouling Rate

Test Fuel	JFTOT Breakpoint	Fouling Rate at 200°C (392°F)	Percentage Effect
AL-25018	263°C (505°F)	0.0093	Baseline
AL-25018 + 0.5 vol % DF	245°C (473°F)	0.0184	97% increase
AL-25017	268°C (514°F)	0.0068	Baseline
AL-25017 + 1.5 vol % DF	255°C (491°F)	0.0140	105% increase
AL-25017 + 1.5 vol % DF + 247 mg/L SPEC AID 8Q462	285°C (545°F)	0.0007	95% decrease

This shows that a small percentage of diesel/fuel oil contamination can cause a jet fuel to go off-spec with regard to thermal stability. More importantly, it demonstrates that the +100 additive, SPEC AID 8Q462, can be very effective at improving thermal stability and restoring fuel quality, at least for this type of contamination. In this case the fouling rate was reduced by a factor of 20.

Effect on Partially Fouled Fuel Nozzles - The evaluation of A-1 for its ability to clean a fouled nozzle was conducted on a nozzle that had been fouled in an earlier test. The nozzle had an original flow number of 2.42 which had been reduced to 2.21 during the previous testing. JP-8+100 was flowed through the nozzle at a fuel temperature of 149°C (300°F); otherwise, the test conditions remained the same as in the nozzle fouling tests. This temperature was chosen because it represented a realistic operating fuel temperature.

Figure 66 presents the historical record of the flow number over a period of 40 hours. During this period, there was essentially no change in the flow number. It was therefore concluded that JP-8+100 using A-1 cannot be expected to clean up a used and partially fouled fuel nozzle.

Red-Dye Contaminated Fuels - To evaluate the potential effect of red dye contamination on nozzle fouling, two of the JP-8 test fuels were contaminated with red dye at a concentration of 0.55 mg/L. Neither fuel was found to have a change in breakpoint temperature. One of the fuels, AL-25017, was arbitrarily selected for nozzle fouling tests to see if the lack of effect on the JFTOT test would be realized in a hardware test. Figure 67 compares the nozzle fouling rates of this fuel with and without the red dye. The fouling rates and the temperature sensitivities are virtually identical. This does not mean that the F110 fuel nozzle would not be sensitive to red dye contamination; it simply means that in this case there was agreement between the JFTOT and the fuel nozzle as to the effect of red dye on the deposit forming characteristics of the fuel.

Overall Sensitivity of Nozzle Fouling to JFTOT Breakpoint Temperature - Referring back to Figure 63, it seems apparent that the data sets not only have similar slopes, but, with the exception of Fuel No. 5 as previously discussed, are fairly well ordered according to JFTOT breakpoint temperature.

Figure **68** presents a correlation of the fouling rates, FR, of the various fuels at a fuel temperature of 200°C (39°F) with the JFTOT breakpoint temperature of the fuel; Fuel No. 5 was excluded from this correlation.

This correlation is quite good, suggesting a relationship of the following form:

$$FR = f\ [A x \exp(-B x T_{BP})]$$

This relationship can be used to estimate the impact of the two-tiered JFTOT on the fouling rate of F110 fuel nozzles. Table 34 gives the fouling rates from this equation for three relevant breakpoint temperatures.

Table 34 Effect of JFTOT Breakpoint Temperature on F110 Nozzle Fouling Rate at T_{fuel} = 200°C

T_{BP}, °C (°F)	Fouling Rate
245 (473)	0.0346
260 (500)	0.0098
275 (527)	0.0028

This says that a decrease in breakpoint temperature of 15°C (27°F) would increase the fouling rate by a factor of 3.5. This means that a fuel that failed the JFTOT at 260°C (500°F) but passed at 245°C (473°F) could cause the fouling rate for F110 engines to increase by a factor of about 3.5. The potential impact of using 245°C fuel is even greater when compared to a JP-8 of average thermal stability rather than a minimum. Most refineries test JP-8 for thermal stability at 275°C (527°F) rather than the minimum of 260°C to allow for possible degradation after leaving the refinery. According to a recent DESC survey, over 70% of JP-8 has a JFTOT breakpoint of 275°C or greater. Compared to this average, using a fuel of only 245°C would cause an increase the fouling rate of F110 fuel nozzles by a factor of about 12.4.

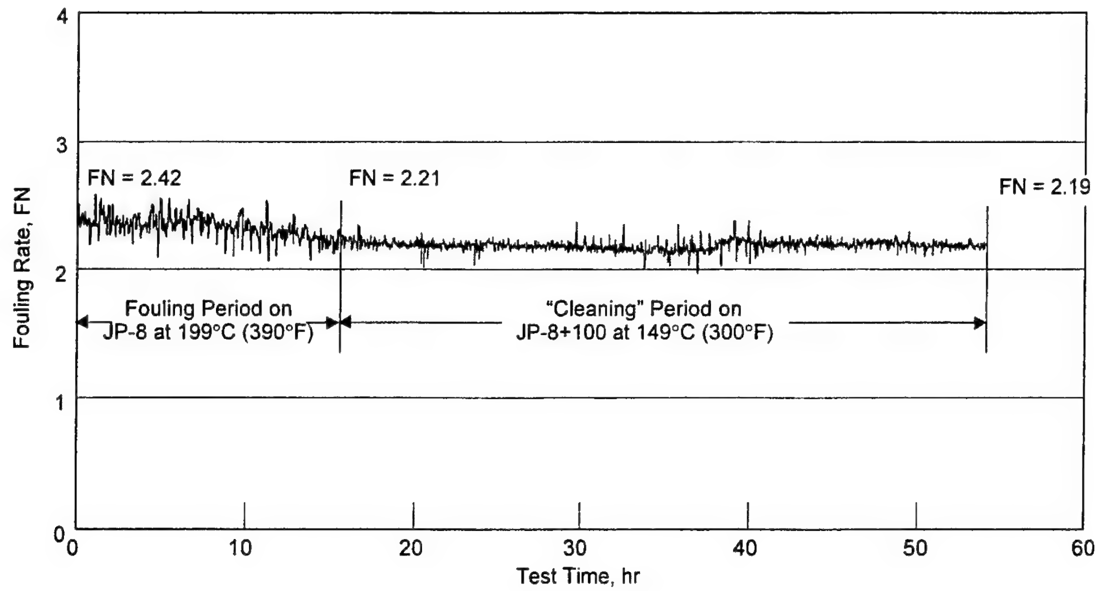


Figure 66 Test Results for Attempt to Clean a Fouled Nozzle with JP-8+100

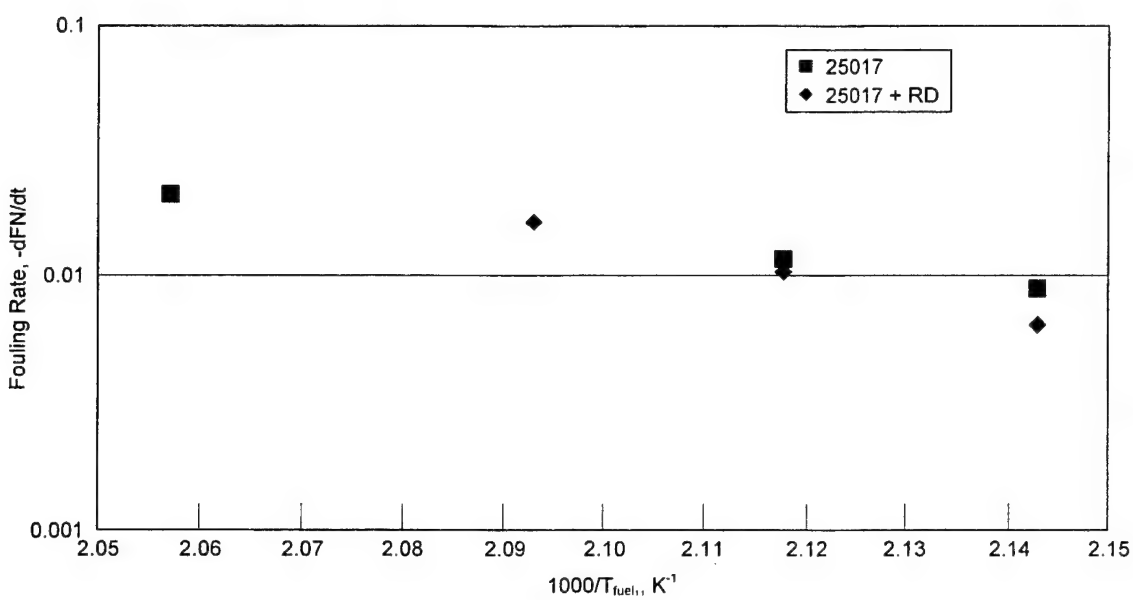


Figure 67 Effect of Red-Dye Contamination on Fouling Rates for One Test Fuel

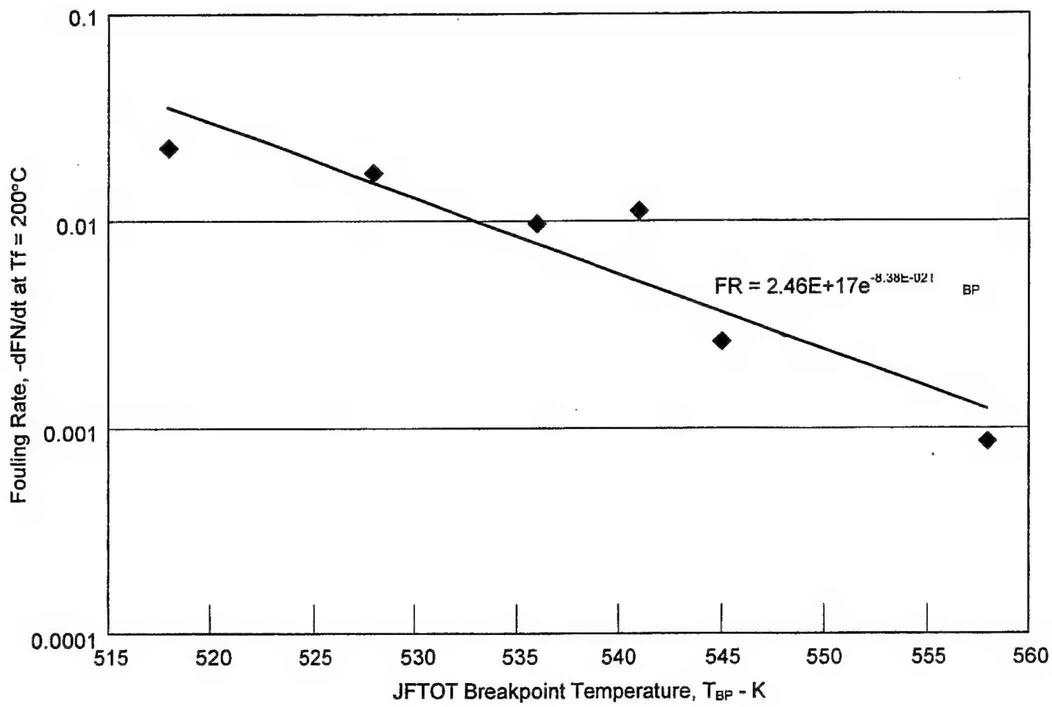


Figure 68 Correlation of Fouling Rates for All Test Fuels at a Fuel Temperature of 200°C (392°F)

Effect of SPEC AID 8Q462 on Allowable Fuel Temperature - A comparison of the fouling rates between Fuels Nos. 6 and 7, which differ only by the use of SPEC AID 8Q462, confirms that the use this additive will allow an increase in fuel temperatures. Figure 69 (deleted) replots the fouling-rate data for these two fuels and shows that at a fouling rate of 0.001, SPEC AID 8Q462 allows an increase of fuel temperature from 161° to 205°C (322° to 401°F) without an increase in fouling rate. This is close to the 55°C (100°F) increase intended by the +100 concept. It must be pointed out that small changes in the slopes of these data sets would affect this ΔT. Also, it is not known how changes in flow rate, such as operation at power conditions other than the beginning of idle descent, would affect the sensitivities of fouling rate to fuel temperature and breakpoint temperature. Therefore, at this point, it is considered quite positive that the temperature increase is of the order of 55°C (100°F).

Effect of SPEC AID 8Q462 on Fuel-Wetted Wall Temperature

A series of parametric deposition tests were to determine how much the use of JP-8+100 would allow fuel-wetted wall temperatures to be increased without increasing deposition rates. The test rig was the SHiQ as described on page 1. The effect of SPEC AID 8Q462 was evaluated at two fuel temperatures bracketing current practice, 149°C and 177°C (300°F and 350°F); at each temperature, a series of SHiQ tests were conducted at wall temperatures ranging from 288° to 399°C (550° to 750°F). The results of these tests are presented in Figure 70 (deleted).

The results of the tests are as would be expected. Deposition rates increased with both fuel temperature and wall temperature. The additive proved to be very effective at reducing the deposition rate, especially at high wall temperatures. Comparing the data at the T_{fuel} = 177°C (350°F), the deposition rate for JP-8+100 at T_{wall} = 399°C (750°F) is about the same as that for JP-8 at T_{wall} = 343°C (650°F), that is an increase of about 55°C (100°F). A comparison at T_{fuel} = 149°C (300°F) or at lower, perhaps more realistic, wall temperatures, is difficult because of the data scatter at low deposit rates; this scatter is because the small amount of deposit present is in the range of sensitivity for carbon burnoff. But nevertheless, a significant increase in allowable wall temperature is indicated with the use of SPEC AID 8Q462. The increase is definitely dependent upon both fuel and wall temperatures. Since tests were conducted only at one flow rate, it is not known whether the results might be influenced by fuel flow rate.

Tertiary-Cavity Pyrolysis

The tests to evaluate the effect of JP-8+100 on fuel pyrolysis in tertiary cavities of fuel nozzles were conducted in the test rig described on page 1. Tests were conducted for periods of 1, 50, 100, 300, and 500 hours using a JP-8 fuel with and without the SPEC AID 8Q462 additive to develop data on pyrolysis rates as well as the effect of the additive. The test cavity was oriented horizontally; as a result, the deposits on the bottom appeared to be a little darker than the deposits on the top. Visually, there was just a faint darkening of the wall, like a dusting of carbon on it, indicating that the deposits were very thin. Generally, the deposit was darker on the bottom half than on the top half.

Figure **71** shows the effect of the additive on the deposit rates for the four areas evaluated that is at the center and at the end of both the top and the bottom of the cavity. At the two locations the results are quite comparable with slightly higher deposition rates on the bottom surfaces than on the top. In all cases, the deposition rates go down dramatically with time. Overall, the tests with JP-8+100 resulted in consistently lower deposition rates, although the effect is not large.

Summary

Fuel nozzles from the F110 engine have been used to conduct fouling studies to:

- evaluate the potential significance to the Air Force of the two-tiered JFTOT system in civilian aviation fuel and
- demonstrate the effectiveness of JP-8+100 to improve Jet A fuels which pass the JFTOT at 245°C but fail to meet the JP-8 requirement for thermal stability.

A 245°C jet fuel was found to cause a measurable increase in nozzle fouling rate. At the standard treat rate of 256 mg/L, the JP-8+100 additive SPEC AID 8Q462 was found to be very effective for improving a fuel that was off-spec on thermal stability due to contamination. The ability to permit higher fuel temperatures and/or wetted wall temperatures was also demonstrated and quantified. The effect on pyrolysis in tertiary cavities was also investigated, and while there was a consistent reduction in wall deposit, the effect was small.

The nozzle fouling tests were conducted by operating the test nozzles in an environment that simulated the thermal and flow conditions of engine installation at the beginning of idle-descent. The fuel temperature was elevated above normal operating temperature as a means to accelerate fouling and reduce test times.

The test fuels consisted of JP-8 fuels either unaltered or contaminated with either diesel fuel or red dye. SPEC AID 8Q462 was the only thermal-stability additive evaluated.

As expected, nozzle fouling rates were found to increase with increasing fuel temperature and decreasing JFTOT breakpoint temperature, a measure of fuel thermal stability. Nozzle fouling rates were found to be exponential with inverse fuel temperature, showing that at constant flow conditions, fouling is kinetic controlled. The Arrhenius plots showed that the kinetics were not altered by the increased fuel temperature. With one exception, the fouling-rate

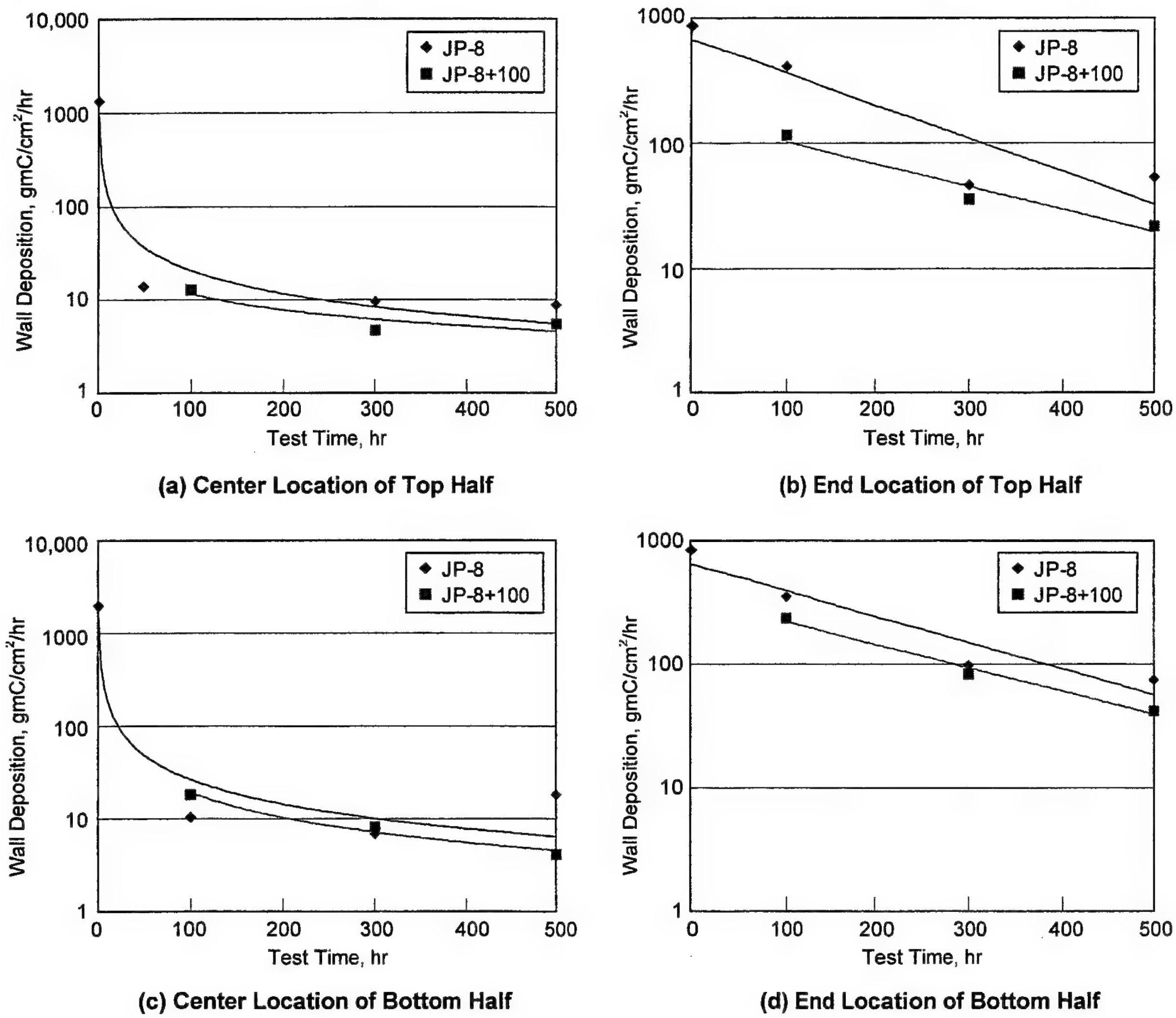


Figure 71 Effect of SPEC AID 8Q462 on Pyrolysis Deposition in Simulated Tertiary Cavity at Four Locations

characteristics of the test fuels were fairly well ordered according to JFTOT breakpoint temperature, regardless of whether the fuel was neat, contaminated, or additized. Moreover, the Arrhenius plots for the various fuels had very similar slopes, suggesting a similarity of global kinetic mechanism for deposition among the fuels. This also suggests that there is a metric for fuel thermal stability that can be related to nozzle fouling rates. JFTOT breakpoint temperature appears to be a good candidate, but is not necessarily the best; it was simply the only one evaluated.

It was found that a jet fuel which fails the JFTOT at 260°C (500°F), but passes at 245°C (473°F), could result in an increase in nozzle fouling rates by a factor of about 3.5 over a minimally acceptable JP-8; as compared to an average JP-8, the increase could be by a factor of about 12.4.

SPEC AID 8Q462 was found to be very effective at improving fuel thermal stability of a JP-8 fuel contaminated with diesel fuel when tested in actual engine hardware, that is, it was not simply "fooling" the JFTOT test; the fouling rate was reduced by a factor of 20. By adding SPEC AID 8Q462 to one of the test fuels at the standard treat rate 247 mg/L, it was found that the additized fuel had the same fouling rate at 205°C (402°F) as the neat fuel had at 161°C (322°F), an effective increase in allowable fuel temperature of 44°C (80°F). In a special rig for evaluating wall temperature effects, it was found that with SPEC AID 8Q462, the fuel-wetted wall temperature could be raised about 55°C (100°F) for the same fouling rate. When flowed through a partially fouled nozzle, JP-8+100 was not found to provide any cleaning action.

Two of the test fuels in this program were evaluated for sensitivity to red dye contamination with the JFTOT; they were found to be not sensitive at 0.55 mg/L of red dye, a concentration equivalent to a contamination of 5% fully dyed diesel fuel. Nozzle fouling tests with one of the fuels also showed no effect at this contamination level. It would require testing with a fuel that the JFTOT indicates is sensitive to red dye to establish that the JFTOT is effective for this problem.

A limited number of tests were conducted to investigate the effect of SPEC AID 8Q462on fuel coking in the tertiary cavities of fuel nozzles that incorporate that design. A series of tests conducted over varying periods up to 500 hours showed that pyrolysis does take place in that environment, but wall deposits were very slight; the deposits were only slightly reduced by the presence of the additive.

Conclusions

This testing program has demonstrated that nozzle tests can be conducted in an environment simulating engine installation to study and quantify factors affecting fouling rates due to high-temperature fuel deposits. The effects of fuel temperature are exponential with fairly consistent activation energies among the fuels tested. From this it is concluded that the kinetics of deposition chemistry were the controlling factor and that among the fuels tested, the global deposition mechanism was effectively the same, regardless of the fuel factors affecting thermal stability, that is: basic fuel chemistry, contaminants, or additives.

While it was possible to quantify the effects of fuel temperature and breakpoint temperature for this nozzle design, in general it is expected that each nozzle design would have its own sensitivities due to unique combinations of the dimensions of the critical flow passages and wetted wall temperatures. Wetted wall temperature is very critical because that is the driving factor for deposition. Beyond that, fuel nozzles with large flow passages, such as low-pressure air blast atomizers, would be expected to be less sensitive than pressure atomizers; similarly, nozzles with high flow numbers would be less sensitive than ones with small flow numbers, assuming the wetted wall temperatures are the same.

The tests showed that a decrease in breakpoint temperature of 15°C (27°F) would result in an increase in fouling rate of 3.5 at a fuel temperature of 200°C (392°F). Thus the potential effect of the two-tiered JFTOT system of the civilian Jet A specification would be to increase the fouling rate by a minimum of 3.5. When a Jet A of minimal thermal stability, i.e., 245°C, is compared to a JP-8 of average thermal stability, 275°C, the effect would be to increase fouling rate by a factor of 12.4.

Using these tests, SPEC AID 8Q462, as an approved additive for JP-8+100, was found to be truly effective at reducing fuel nozzle fouling rates; it did not simply "fool" the JFTOT. When added to a JP-8 contaminated with diesel fuel and failing the JFTOT at 260°C, this additive was found to increase the breakpoint temperature from 255°C to 285°C (491°F to 545°F) and, more importantly, reduce the fouling rate by a factor of 20. This means that the additive could be very useful in improving some jet fuels that have gone to minimum on thermal stability during storage or transport.

As a necessary part of these tests, it was shown that small amounts of diesel fuel on the order of one to 2%, can be very detrimental to the thermal stability of jet fuel. The sensitivity of thermal stability to diesel contamination varies with the jet fuel and of course with the quality of the diesel fuel itself. The diesel fuel used in this study was the Cat-1H high sulfur diesel reference fuel which has a breakpoint temperature around 220°C (428°F). Many low-sulfur

diesel fuels have a thermal stability that is on par with jet fuels, and small contaminations would not necessarily degrade the thermal stability of jet fuel. However, the thermal stability of diesel fuel is not controlled so caution must always be exercised.

The nozzle fouling tests were also able to confirm the potential for increased heat sink with JP-8+100. It was found that for this nozzle under the test conditions, with SPEC AID 8Q462 the fuel temperature could be increased by 80°F without increasing the fouling rate.

In a parallel test with a different rig, it was found that wetted-wall temperatures could also be increased when SPEC AID 8Q462 was used. The allowable increase is very dependent upon both fuel and wall temperatures.

On a more neutral note, when JP-8+100, made from SPEC AID 8Q462, was used in a fuel nozzle that had already experienced some fouling in an earlier experiment, there was no appreciable increase in flow number after 40 hours. It was therefore concluded that JP-8+100 will not clean up used nozzles, it will simply reduce the fouling rate.

It is not known why the one jet fuel of very high thermal stability did not conform to the ordering of nozzle fouling rates with JFTOT breakpoint temperature. It was tested three times, each time resulting in a different set of characteristic fouling rates, although the sensitivity to fuel temperature remained the same. When fouling tests with one of the other fuels was repeated, the results were very close to the original tests. This problem may have been related to one of the additives present in the fuel, such as the FSII; with water contamination in the shipping drums, something unusual could have happened to the fuel to affect deposition.

Since this fuel was the only one tested with high natural stability, it also could be speculated that fuels with very high natural breakpoints are very sensitive to minute contaminations such as might be common to any fuel system; this would suggest that high thermal stability from natural causes, such as highly refined fuels, might not be realized in the fuel system. In contrast, a high thermal stability brought about by an additive such as SPEC AID 8Q462 might be very effective at warding off the effects of such contamination through its active ingredients.

Recommendations

Because of the effectiveness of this type of testing in studying the factors relating to deposition, it is recommended that other potential thermal stability additives be evaluated by this same methodology in order to verify and quantify effectiveness in real engine hardware.

While this study showed that JP-8+100 additives such as SPEC AID 8Q462 could be very effective at improving jet fuels which are marginal on thermal stability, it is not known if they would be effective on other types of contaminants, specifically copper. It is recommended that tests be conducted using fuels that have gone off-spec during storage or handling as opposed to the artificial contaminations employed here. Testing for effectiveness with fuels containing copper contamination are especially encouraged.

Since the real effect of fuel additives, such as FSII, on thermal stability are not known, it is recommended that a series of tests be conducted with FSII in a fuel saturated with water, perhaps after some storage period, or under the conditions where "apple jelly" forms to determine if there are some unknown compatibility problems with additives.

Further evaluation of several fuels with naturally high thermal stability would be useful to determine whether there is something unusual about such fuels such that the high thermal stability measured by the JFTOT is not realized in actual hardware systems, while high thermal stability from an additive remains effective.

3.7.4.2 Fuel Nozzle Tip Heat Transfer Analysis

(DELETED – SEE FULL REPORT)

3.7.5 Task 3.8: Plan Advanced High-Temperature Engine Demonstration

When this contract started, in 1995, GEAE was running an Advanced Technology Demonstrator Engine (JTDE) program. Since then, the technology demonstration programs have become partnerships with other interested companies. As a result, most of the demonstration engines are run at these other-company facilities. Planning the use of these engines to demonstrate fuels technology advances has become much less certain due to ownership issues with the demonstrator hardware and the need to bail fuel storage facilities for the special fuel. Preliminary meetings

with the Engineering Systems Managers of the Advanced Technology Engine Gas Generator (ATEGG) Phase II program and the Joint Strike Fighter (JFS) Engine program were set up to discuss the use of these core programs for demonstrating advanced high-temperature engine use of JP-8+100 fuel. Engine testing would be done at Allison Advanced Technology Division (AADC), Indianapolis, IN. At present, agreement has been reached to run JP-8+100 in these programs, when the schedule permits.

3.7.6 Task 3.10: System Safety Requirements

This activity was started when hardware was delivered to Room 20 Laboratory, during or about June 1997. At that time, *System Safety Reviews* held between the design engineer and the laboratory operators resulted in the placing of safety instrumentation (static pressures and skin thermocouples) on the parts. These items were monitored during initial testing to ensure that no safety limits were exceeded during the course of the standard test series. These test instruments were also checked as new and different operating conditions were set to ensure that proper limits were not exceeded.

4.0 Conclusion and Recommendation

It is concluded that the use of the thermal-stability additive would have a generally positive effect on control and pump components of aircraft engines by significantly reducing dirt and varnish accumulations (which make tear down and inspection of these parts difficult) and that there would be no significant degradation on hot-parts life of the engines or on the rest of the fuel system.

GEAE recommends approval of the use of the thermal-stability additive selected by the Air Force Fuels Branch for all GEAE and CFMI engine models. The approved additive would be SPEC AID 8Q462.

APPENDIX

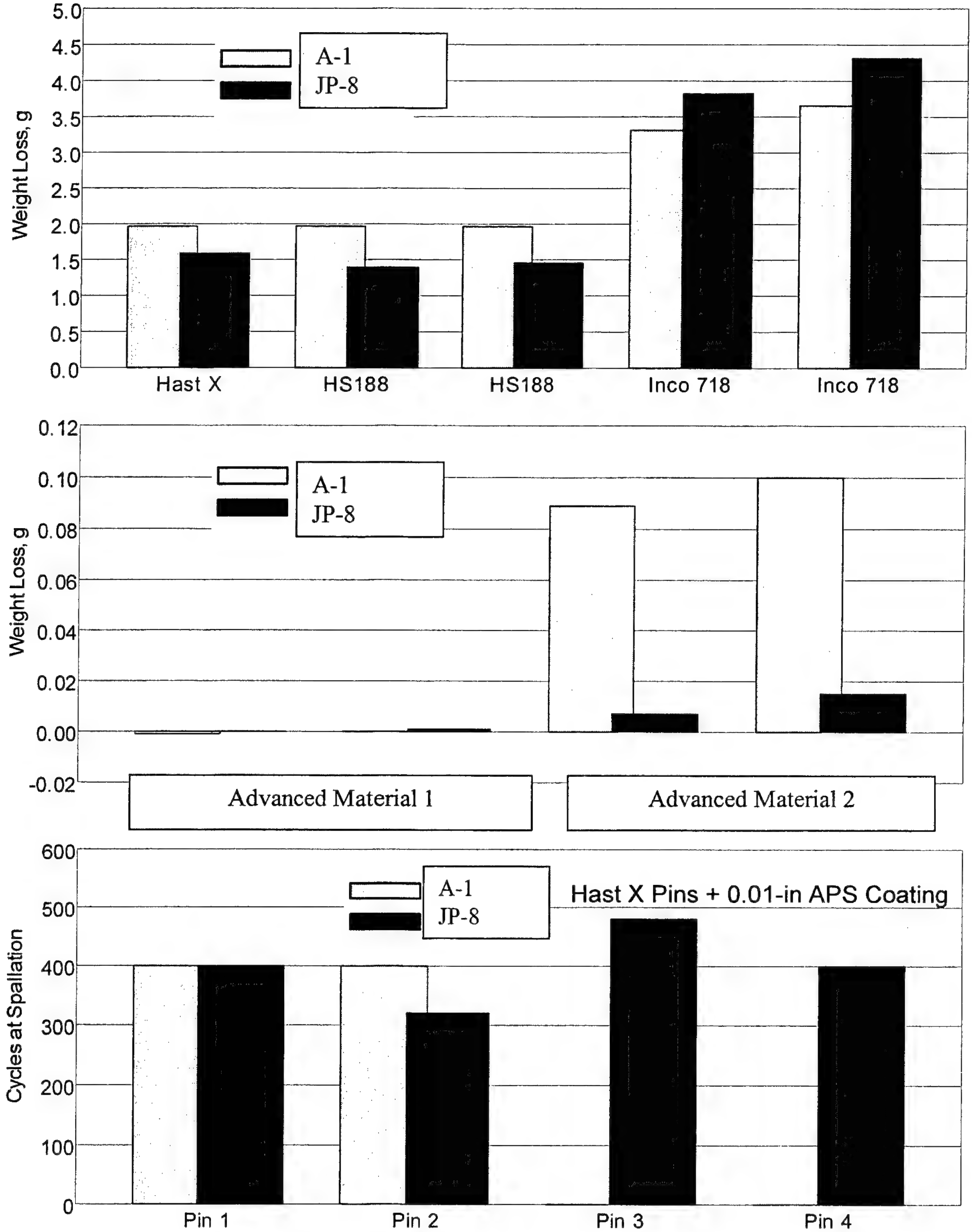


Figure 43 Test 1 and 2 Comparison

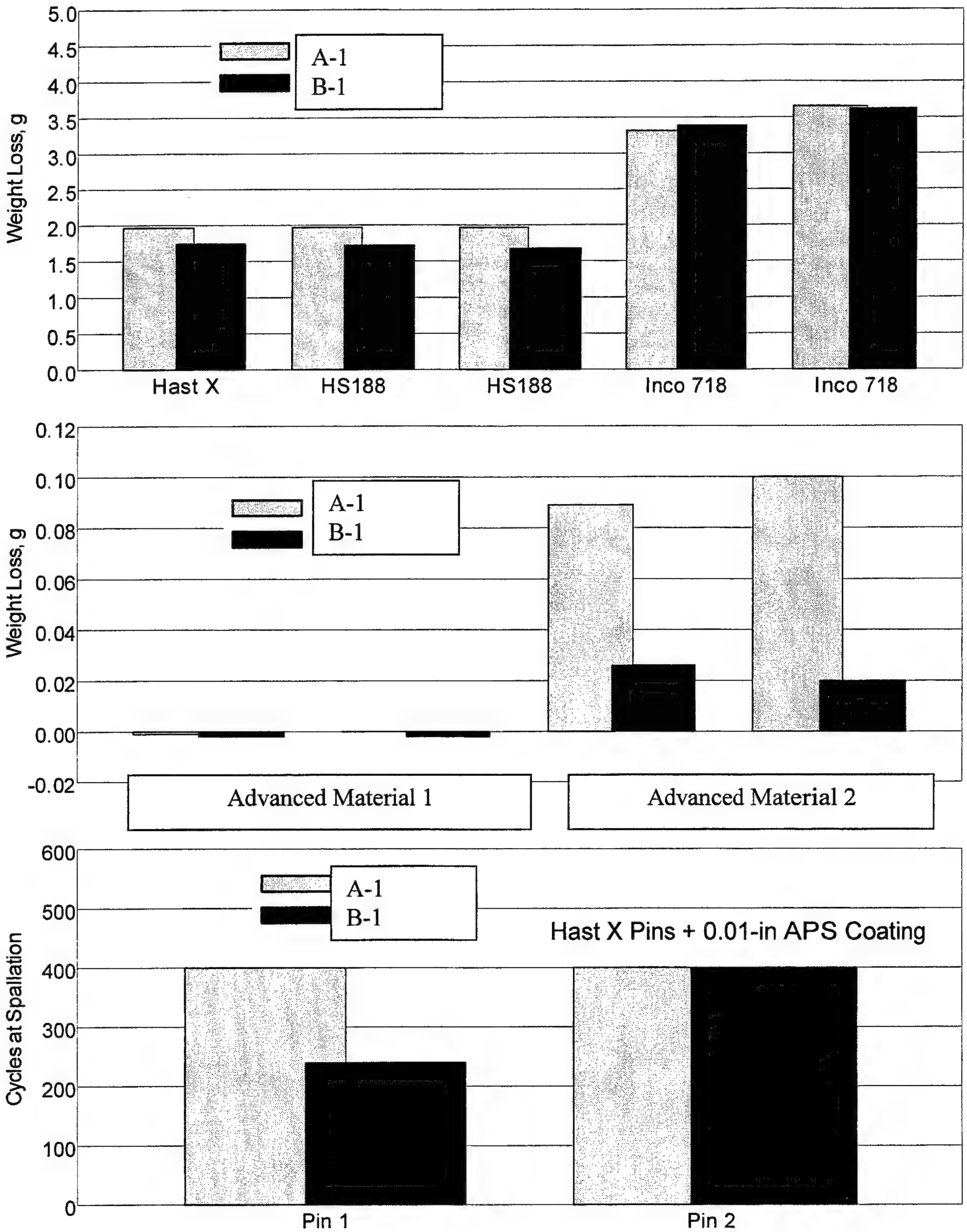


Figure 44 Test 2 and 3 Comparison

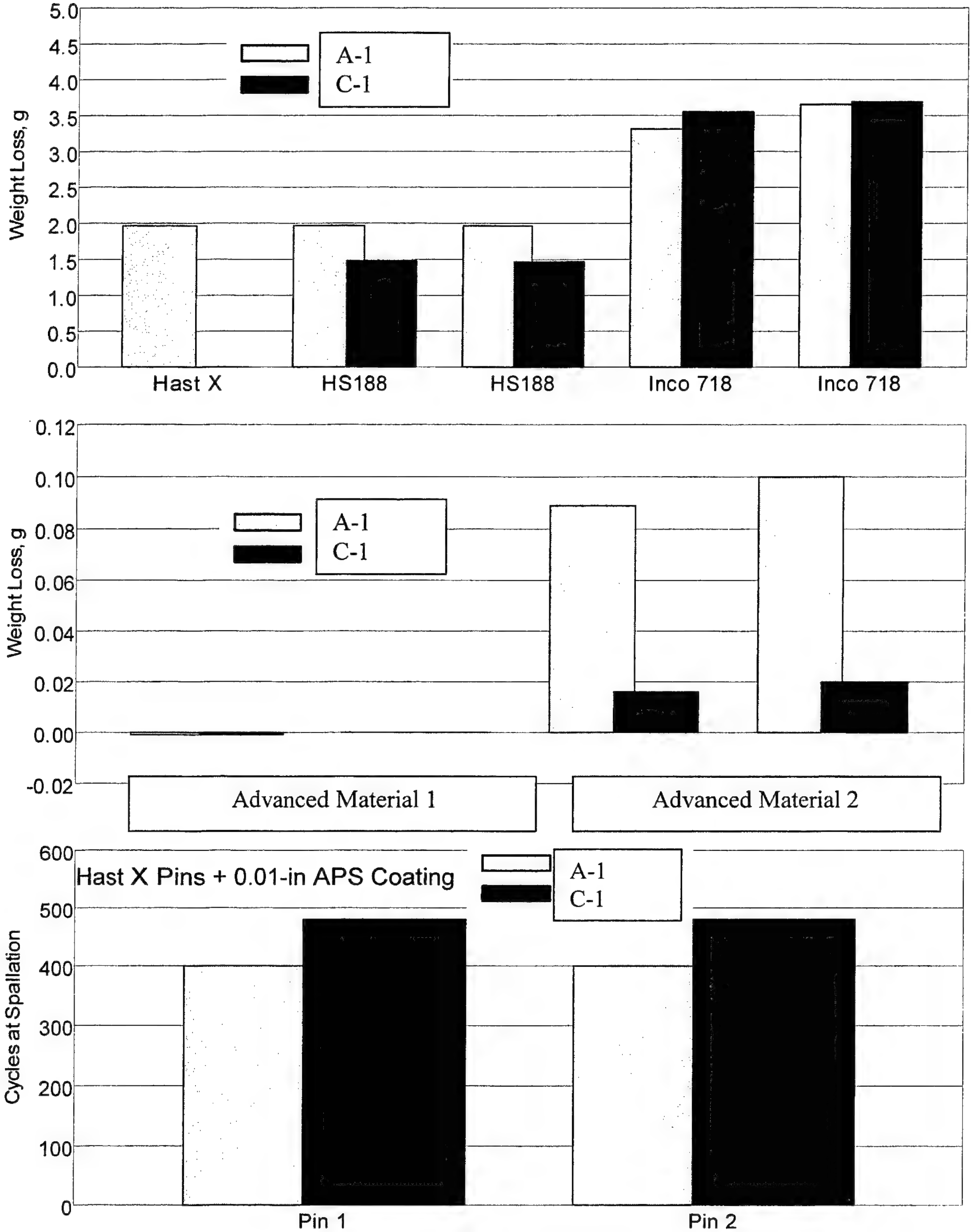
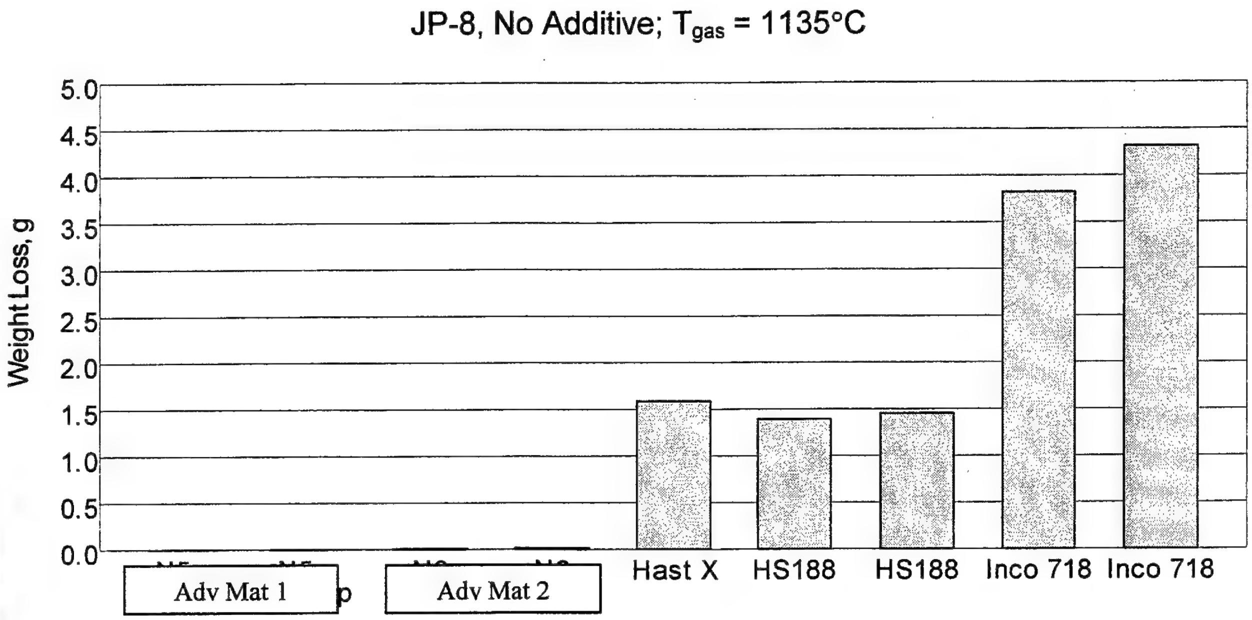


Figure 45 Test 2 and 4 Comparison



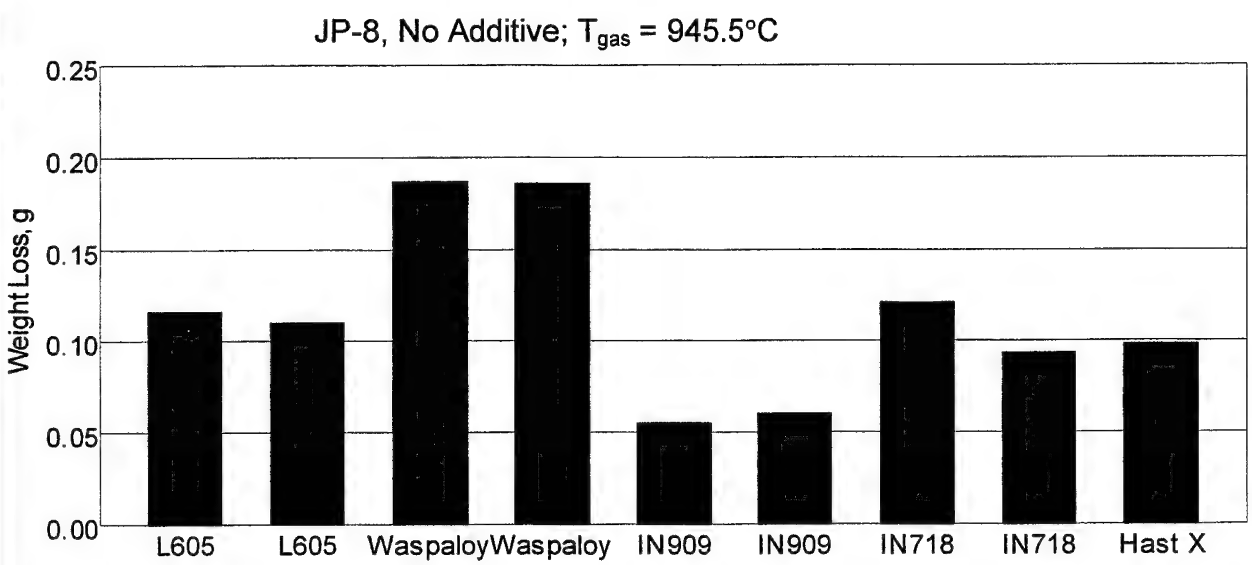


Figure 46 Test 1 and 5 Comparison

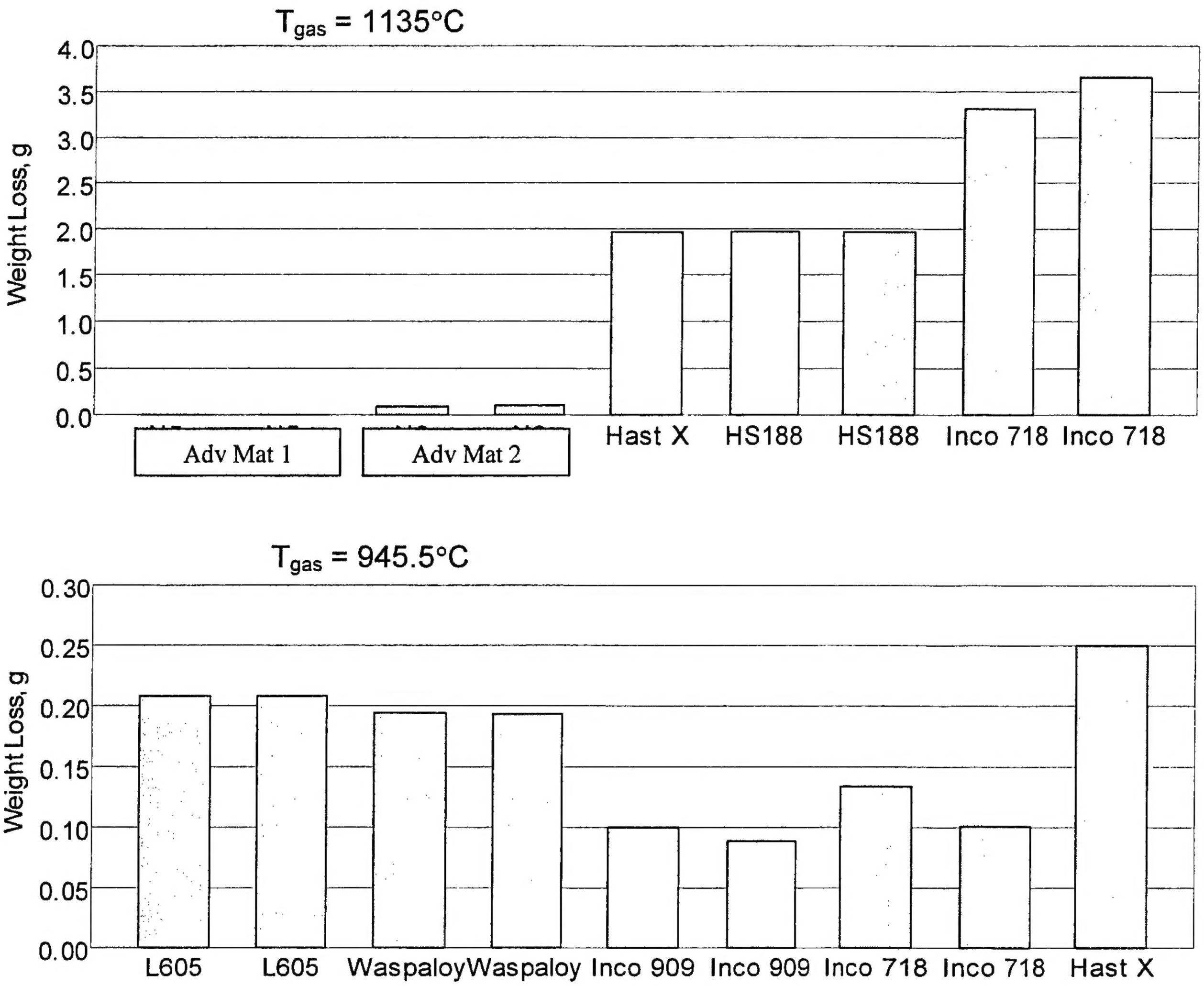


Figure 47 Test 2 and 6 Comparison

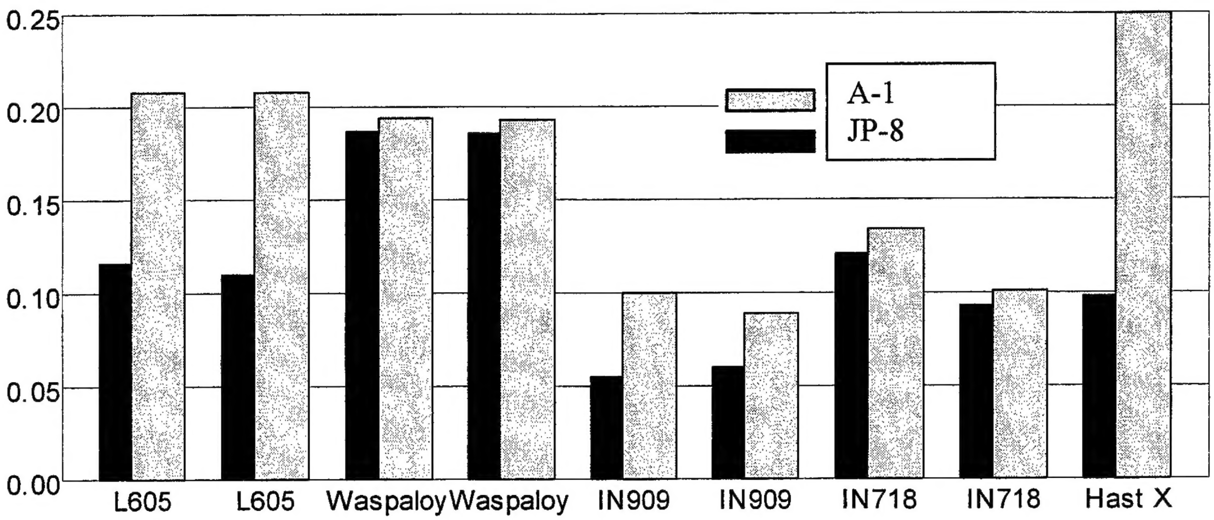


Figure 49 Test 5 and 6 Comparison

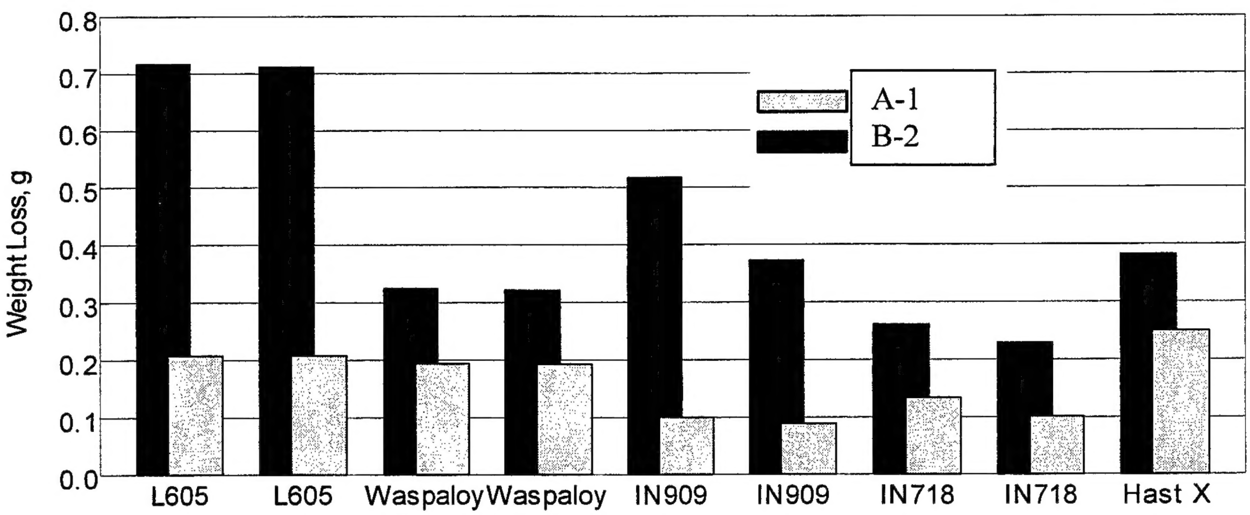


Figure 48 Test 7 and 6 Comparison

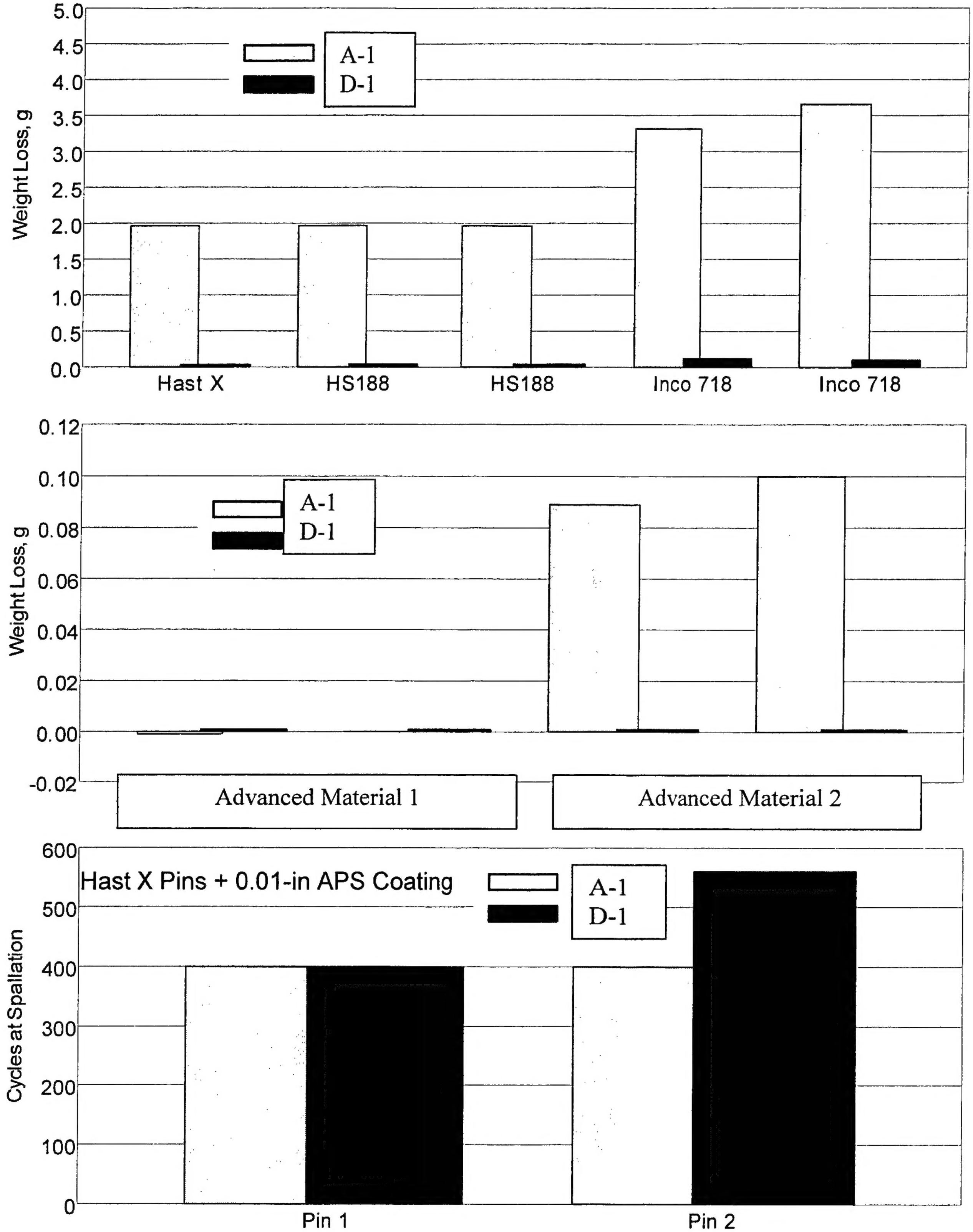


Figure 50 Test 2 and 8 Comparison

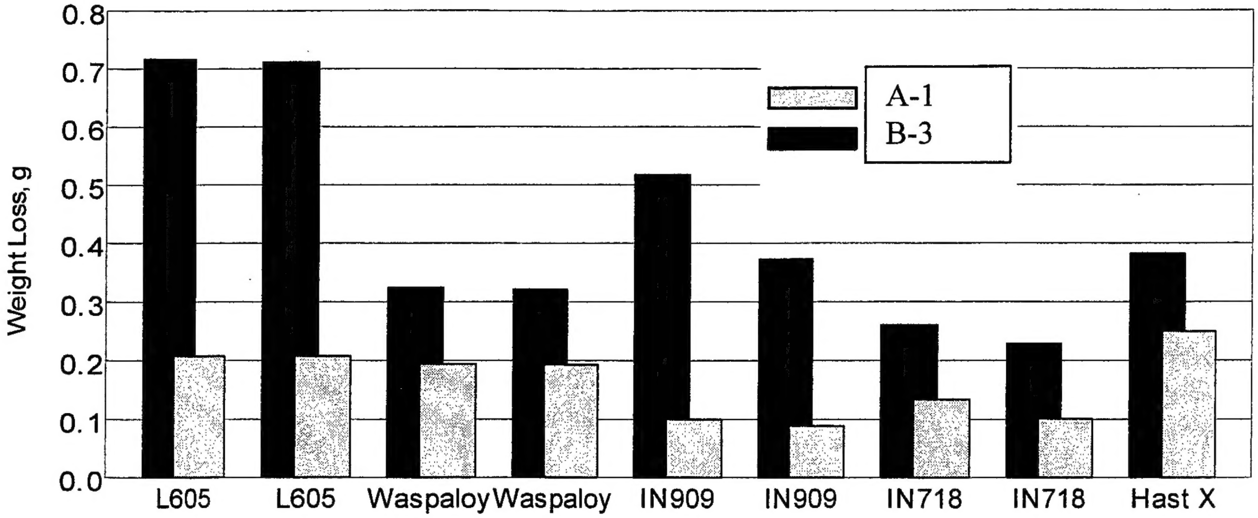


Figure 51 Test 6 and 9 Comparison

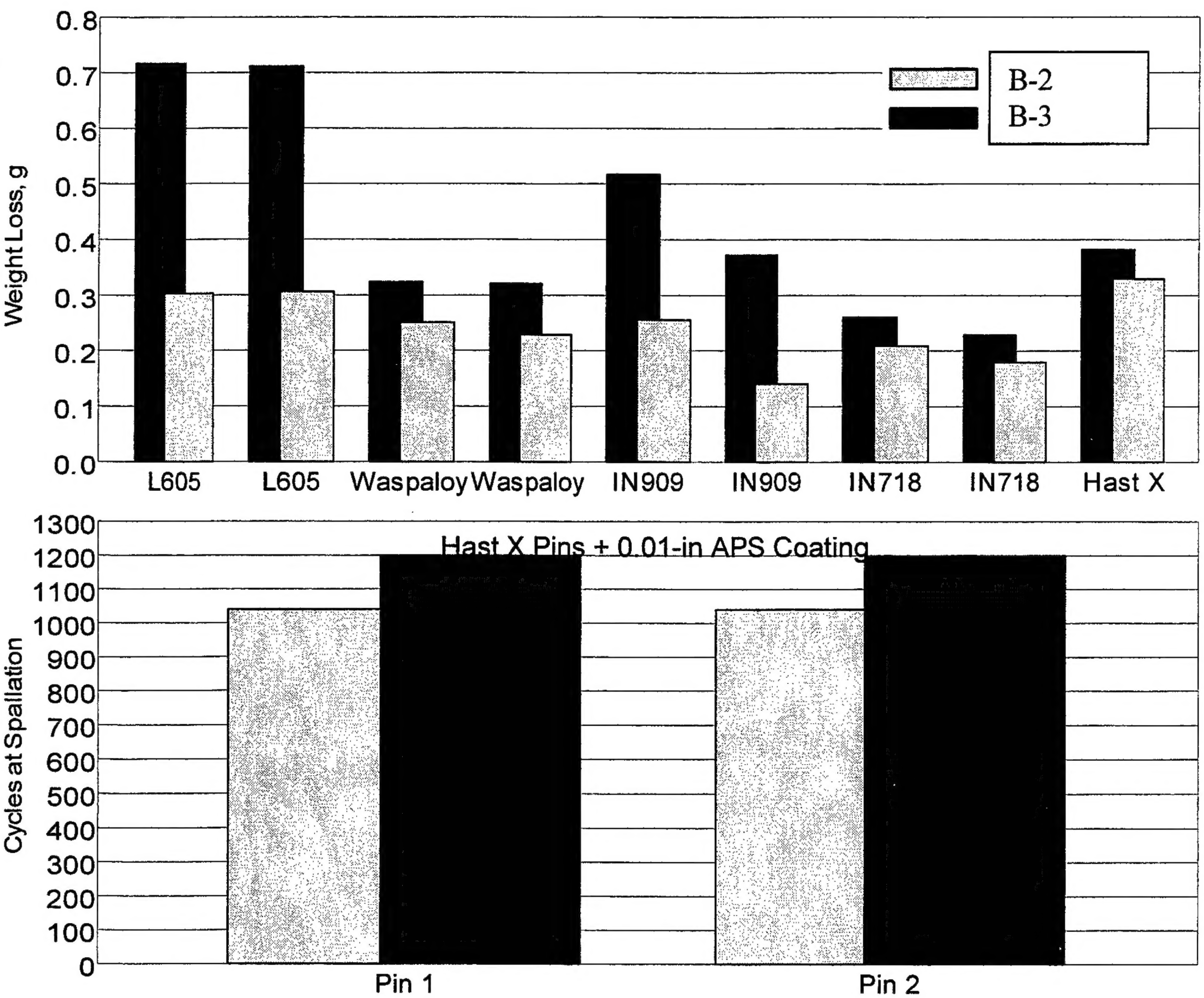


Figure 52 Test 7 and 9 Comparison